Best Management Practices for Implementing Ultra-Early Spring Wheat (*Triticum aestivum* L.) Growing Systems on the Northern Great Plains

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

in

Plant Science

Department of Agricultural, Food and Nutritional Science

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Abstract

Ultra-early planting of spring wheat (*Triticum aestivum* L.) between soil temperatures of 0°C and 7.5°C on the northern Great Plains allows the exploitation of longer growing seasons and the avoidance of the onset of extreme heat later in the season during sensitive physiological growth stages, including flowering and grain filling. Recent studies in western Canada assessed ultra-early planting, and the management practices and wheat cultivars required to successfully implement ultra-early wheat planting on the northern Great Plains. Planting wheat between soil temperatures of 2°C and 6°C optimized grain yield and grain yield stability in western Canada. Planting between 0°C and 7.5°C always resulted in greater grain yield and grain yield stability than delaying planting to a conventional planting time at 10°C soil temperature or higher. Current commercial Canadian hexaploid spring wheat varieties exhibited improved grain yield and grain yield stability when planted ultra-early. No differential in grain yield stability was present between specially-developed cold tolerant wheat lines and current commercial Canadian hexaploid spring wheats. When assessed at ultra-early and conventional planting times, no individual cultivar or group of cultivars representing a Canadian wheat market class, had greater grain yield or grain yield stability when planting was delayed to the conventional time. The grain yield and grain yield stability of ultra-early planted wheat can be improved with the implementation of optimized management practices in an ultra-early wheat growing system. An optimal sowing density of 400 seeds m^{-2} increased grain yield as well as grain yield stability for ultra-early planted wheat. Shallow sowing depths (2.5 cm) did not affect grain yield, but when assessed in combination with optimal sowing rates, improved grain yield stability of ultra-early planted wheat. Spring weed management using fall-applied residual herbicides reduced early season weed pressure, increased grain yield in some locations, and did not negatively affect grain yield stability of ultra-early planted wheat. An optimized growing system for ultra-early planted wheat on the northern Great Plains includes a regionally adapted, competitive, Canadian hexaploid spring wheat cultivar, planted at 2.5 cm depth when soil temperatures are between 2°C and 6°C, at an optimal sowing density of not less than 400 viable seeds m^{-2}. Fall-applied residual herbicides can be safely used in the growing system to manage spring weed pressure if required. Ultra-early wheat growing systems can be immediately implemented to increase grain yield and grain yield stability on the northern Great Plains. Producers adopting ultra-early wheat growing systems will realize additional grain yield and grain yield stability benefits relative to conventional planting with the increases of daily average temperatures and atmospheric CO_2 concentrations predicted to occur over the next thirty years.

Preface

Chapter two of this thesis has been published as G. R. S. Collier, D. M. Spaner, R. J. Graf, and B. L. Beres. The integration of spring and winter wheat genetics with agronomy for ultra-early planting into cold soils. (2020) *Frontiers in Plant Science*. 11:89. doi: 103389/fpls.2020.00089. I was the primary data collector and trial manager at the Edmonton, Alberta trial location. Dr. Beres initially conceptualized this study and managed the Lethbridge, Alberta trial location. Dr. Graf developed the cold tolerant lines used in this study. I analyzed all data with the assistance of Drs. Beres and Spaner and prepared the manuscript for publication. Drs. Spaner, Beres and Graf edited the manuscript. Multiple technical staff supported data collection and trial management at the various trial locations of this study throughout western Canada.

Chapter three of this thesis has been published as G. R. S. Collier, D. M. Spaner, R. J. Graf, and B. L. Beres. Optimal agronomics increase grain yield and grain yield stability of ultra-early wheat seeding systems. (2021) *Agronomy*. 11, 240. doi: 10.3390/agronomy11020240. I was the primary data collector and trial manager at the Edmonton trial location. Dr. Beres initially conceptualized this study and Dr. Graf developed the cold tolerant lines used in this study. I analyzed all data with the assistance of Drs. Beres and Spaner and prepared the manuscript for publication. Drs. Spaner, Beres and Graf edited the manuscript. Multiple technical staff supported data collection and trial management at the various trial locations of this study throughout western Canada.

Chapter four of this thesis has been published as G. R. S. Collier, D. M. Spaner, R. J. Graf, C. A. Gampe, and B. L. Beres. Canadian spring hexaploid wheat (*Triticum aestivum* L.) cultivars exhibit broad adaptation to ultra-early wheat planting systems. (2022) *Canadian Journal of Plant Science*. 102: 442-448. doi: 10.1139/cjps-2021-0155. I was the primary data collector and trial manager at the Edmonton trial location. Ms. Gampe was the primary trial manager at the Scott, Saskatchewan location. I conceptualized this study with the assistance of Drs. Spaner and Beres. Dr. Graf developed the cold tolerant wheat lines used in this study. I analyzed all data and prepared the manuscript for publication with the assistance of Drs. Beres and Spaner. Drs. Beres, Spaner and Graf and Ms. Gampe edited the manuscript. Multiple technical staff supported data collection and trial management at the Edmonton, Scott, and Lethbridge locations of this study.

Chapter five of this thesis has been published as G. R. S. Collier, D. M. Spaner, L. M. Hall, R. J. Graf, and B. L. Beres. Fall-applied residual herbicides improve broadleaf weed management in ultra-early wheat (*Triticum aestivum* L.) production systems on the northern Great Plains. (2022) *Canadian Journal of Plant Science* 102: 1115-1129. doi: 10.1139/cjps-2022-0036. I was the primary data collector and trial manager at the Edmonton trial location. I conceptualized this study with the assistance of Drs. Hall and Beres. Dr. Graf developed the cold tolerant wheat lines used in this study. I analyzed all data and prepared the manuscript for publication with the assistance of Drs. Beres and Spaner. Drs. Beres, Spaner and Hall edited the manuscript. Multiple technical staff supported data collection and trial management at the Edmonton, Scott, and Lethbridge locations of this study.

For my Grandpa, Robert (Bob) Graham Lewis (1922-2019).

Thank you for bringing agriculture into my life.

Acknowledgements

My sincere thanks and gratitude to my co-supervisors Dean Spaner and Brian Beres. You agreed to take me on as a student and mentor me through this project knowing it would be a long process, and understanding that my commitments to my career, family and farm would create challenges along the way. Your expertise and guidance were invaluable, and I would not have completed this work without your encouragement, understanding and supportive persistence.

I was fortunate to have support from many at the University of Alberta who may have been mentors one day, and friends and colleagues the next. Thank you to Dr. Rong-Cai Yang and Dr. Linda Gorim for your support, activity on my committee, and interest in this work. Thank you to Dr. Linda Hall for her consistent support throughout this project as an examining committee member, course mentor, and sounding board. Thank you to Dr. Miles Dyck for mentoring me through a soil fertility course and for being a member of my examining committee.

I'm grateful for the support of many researchers, technical staff and students at the University of Alberta, Agriculture and Agri-Food Canada – Lethbridge and Scott and at the other locations throughout western Canada responsible for trial work in this project. My thanks to Ryan Dyck, Steven Simmill, Warren Taylor, Adam Fast, Craig Stevenson, Cindy Gampe, Arlen Kapiniak, Klaus Strenzke, Dr. Muhammad Iqbal, Fabiana Dias, Joseph Moss, Tom Keady, Izabela Ciechanowska, Lindsay Jessup, Katherine Chabot, Russell Puk, Dr. Hua Chen, Darcy Bemister, Dr. Hiroshi Kubota, Dr. Enid Perez Lara, Keith Topinka, Elise Martin, and Bryanna Jeske among many others.

Thank you to the funding bodies who made this work possible - the Alberta Crop Industry Development Fund, Western Grains Research Foundation, and the Alberta Wheat Commission.

Thank you to my family - my mom and dad Barb and Steve, sister Erinn, and mother-in-law and father-in-law Charleen and Lloyd for your encouragement and enthusiasm.

To my wife Erin, I can't thank you enough for your editing expertise, but I am forever in your debt for all the time I spent in front of a computer or in a field rather than with our family. I would never have completed this without your patience, help and support. To our new daughter Rhett, welcome to our lives, I hope one day you love and respect agriculture as much as your mom and I do.

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1.1 Introduction

Spring wheat (*Triticum aestivum* L.) was initially introduced to the northern Great Plains region of Canada in 1813, and continues to be a socially and economically important crop in the region (Buller 1919, Statistics Canada 2021). In 2019, total wheat production in Canada was 32.3 M MT from a harvested area of 9.66 M ha (FAOSTAT 2021). Ninety-four percent of total Canadian wheat production in 2019 originated within the northern Great Plains region of Canada in the provinces of Alberta, Saskatchewan and Manitoba (Figure 1-1) (Statistics Canada 2021). Of the total wheat production in Canada in 2019, 95% was from varieties exhibiting a spring growth habit; these cultivars do not have a specific vernalization requirement and are sown in the spring and harvested in the fall of the same year. Spring wheat production in the northern Great Plains region of Canada includes two main species of spring wheat, *Triticum aestivum* L. and *Triticum turgidum* L. *ssp. durum* (Statistics Canada 2021). The primary differences between these species include a hexaploid genome in the former (2n=6x=42; AABBDD), a tetraploid genome in the latter (2n=4x=28; AABB), and differing agronomic adaptations, grain quality parameters, end use products and markets (Matsuoka, 2011). Hexaploid spring wheat varieties accounted for 79% of wheat production in Canada in 2019 and were sown on 7.6 M ha, 75% of the total area sown to wheat of any type in Canada (Statistics Canada 2021).

Spring wheat grain production in Canada has increased despite a reduction in area planted. Canada produced an average of 14.3 M MT of grain from spring wheat plantings from 1961 to 1970 and an average of 19.8 M MT of grain from 2008 to 2017. This greater level of production was achieved on an average of 31% fewer hectares between 2008-2017 relative to 1961-1970. Despite the increase in grain yield and efficiency over this time, the Food and Agriculture Organization of the United Nations (FAO) has indicated that by 2050 the global requirement for agricultural products will have increased by an additional 70% from the 2005-2007 levels (FAO 2009). An estimate by Alexandros and Bruinsma (2012) indicated the global demand for cereal grains would increase by one billion MT per year to a total of approximately 3 billion MT per year by 2050; current agricultural systems will be required to increase production using fewer resources, and concurrently adapt to a changing climate. In order to realize these production demands, and maintain or increase the stability of cereal growing systems, it has been proposed that synergistic Genotype (G) × Environment (E) × Management (M) interactions can be exploited to shift global cereal production closer to calculated yield potentials (Beres et al. 2020, Beres et al. 2020a, Porker et al. 2020, Hatfield and Beres 2019, Kirkegaard 2019, Hunt et al. 2018, Kirkegaard and Hunt 2010). The evolution of wheat production in western Canada is more extensive than any other crop in the region, save the harvest of native grassland by native and domestic grazing mammals. There is a rich history of improving the quantity, quality and efficiency of wheat production through manipulations to G × E × M interactions initiated by producers, governments, end users and more recently public opinion.

This review has been generated over 200 years after wheat was first planted in western Canada and farmers, researchers and agronomists began to evaluate interactions of G × E × M in order to optimize grain yield. Wheat remains one of the most important crops grown in the region and an essential source of energy for the human and animal population of the world. This review will explore key evolutionary segments in the history of wheat production in western Canada and outline pending challenges to wheat production that require further adaptation and evaluation of the current understanding of G × E × M interactions in the region.

1.2 Wheat comes west

1.2.1 Initial wheat production in western Canada (1812-1842)

The first recorded production of wheat west of the present-day Ontario – Manitoba border occurred in 1812 at the direction of Lord Selkirk near what is now the city of Winnipeg (Buller 1919, Pattan 2013). Winter growth habit wheat brought with settlers from Scotland was planted in the fall of 1812, and spring growth habit wheat was planted in the spring of 1813 into hand broken plots. Breaking the local prairie soil is perhaps the first example in western Canada of a management tactic being used to improve the cultivation of wheat. A successful harvest was not achieved until 1815 due to combinations of extreme temperatures, hail, frost and pests (Buller 1919, Pattan 2013). Pattan (2013) identified four main geographical and political issues that needed to be overcome at the time before wheat could successfully expand into the northern Great Plains of western Canada and allow the development of one of the world’s largest current wheat producing regions. Pattan's four requirements were settlement of the region and organization as a federal jurisdiction of Canada, successful proof of the ability to grow milling quality wheat in the region, a transportation system to move wheat from the region to world markets, and finally, the prior success of wheat production on the Great Plains in the United States of America, which was already underway at the time. It took a majority of the next 100 years to successfully meet these four requirements in western Canada.

Wheat planting continued each year at the Manitoba settlement with varying success until 1820, at which point the supply of seed wheat for the following season had been exhausted (Buller 1919, Symko 1999). In order to be able to continue sowing wheat, members of the settlement travelled to Prairie du Chien, Wisconsin, returning in June of 1820 with a variety of spring growth habit wheat commonly seeded in Wisconsin at the time (Symko, 1999). The identity of this variety is unknown, and its introduction into western Canada was a necessity caused by the loss of the settlement's seed source, however, this may be the first example of a new, locally adapted wheat variety being introduced into the region.

1.2.3 Introduction of 'Red Fife' hard red spring wheat - 1842

The introduction of 'Red Fife' wheat occurred in 1842 and became the basis for the development of hard red spring-type wheat that has since dominated Canadian wheat production (Buller 1919, Clark 1936, Paulsen and Shroyer 2008). David Fife, of Otonabee, Ontario is credited as the first person to cultivate Red Fife wheat in North America (Buller 1919, Symko 1999). The account of George Esson, reported in the 1861 edition of *The Canadian Agriculturist*, details the circumstance of the first planting of the wheat that would become known as Red Fife, and was recounted by Buller (1919) and Symko (1999). David Fife received a shipment of seed wheat from Danzig, (now Gdansk, Poland) via a contact in Glasgow, Scotland. The seed arrived in Canada in the spring of 1842, and Fife was unaware if the wheat was of spring or winter growth habit. Fife planted a portion of the seed that spring and only one plant transitioned to reproductive growth, resulting in three spikes. Fife harvested and maintained the seed of this plant for planting the following spring. The plants resulting from the spring 1843 planting of this retained seed exhibited resistance to stem rust (*Puccinia graminis*) which had infected the winter-type wheats grown on the remainder of Fife's farm. The evident rust tolerance of the spring growth habit wheat he had selected the past summer led Fife to retain and multiply this seed, establishing the variety to become known as Red Fife. Buller (1919) contends that no evidence has been found that the original spring-type plant was of the same background as the seed wheat it was shipped with, and could have been an accidental cross or an off-type within the original sample. Symko (1999) traces the likely heritage of Red Fife to the Ukrainian variety 'Halychanka'; this is supported by Paulsen and Shroyer (2008) who attribute the success of Red Fife to the similarities between the Ukrainian Steppes and the prairies of the North American Great Plains.

Red Fife was the first major spring growth habit variety suitable for production on the northern Great Plains. By 1860 Red Fife was being grown in eastern Canada and at least 19 states and ultimately it became the dominant hard spring wheat variety in the region (Buller 1919, Symko 1999, Olmstead and Rhode, 2002). In 1876 seed of Red Fife was transported back from Manitoba to Ontario for use as seed stock. Symko (1999) states that there is no record of the first Red Fife production in Manitoba but this movement of seed back to Ontario was the first confirmation of the cultivation of Red Fife in western Canada.

1.2.4 Wheat production expansion in western Canada (1871-1910)

In 1871 the total area devoted to wheat production east of Manitoba was 666,713 ha with a total grain yield of 455,277 MT; wheat production west of Ontario was considered so minor it was not reported (Bishop 1912). Increases in the area used for wheat production from Manitoba east largely stalled between 1880 and 1900. 735,000 MT of wheat was produced on 781,000 ha in 1880 and by 1900 776,000 MT of wheat was produced on 603,000 ha (Bishop 1912). The trend of decreases in the area planted to wheat in eastern Canada continued into the early 20th century. By 1910, only 295,000 ha of arable land was devoted to wheat production east of Manitoba; the decline, according to Bishop (1912) was driven by a shift in wheat production west. Table 1-1 illustrates the progression of total area planted to wheat in western Canada from 1900 to 1911 as reported by Bishop (1912). The area planted to wheat in western Canada from 1900 to 1910 increased by 236% up to a total of 3,398,947 ha (Table 1-1). A majority of this planted area was in Manitoba and Saskatchewan, as settlement was still underway in Alberta. In 1910, Alberta only accounted for 215,789 ha (6%) of the area planted to wheat (Table 1-1). Over this same period the average realized grain yield for the region increased by 63% from 0.63 MT ha^{-1} to 1.03 MT ha^{-1} (Table 1-1). In 1909 Canada produced 4,539,310 MT of wheat in total relative to the 19,410,163 MT produced in the United States the same year. This period of wheat cultivation expansion in western Canada gave great promise to new settlers from Europe and the United States and drove the settlement of the western provinces. Bishop (1912) quotes a report that Carleton (1910) presented to the United States Millers' National Federation Mass Convention of 1910 in which Carleton states, "a careful study of the conditions in Canada reveals a possibility in increased production far ahead of any other present (wheat) exporting country."

1.3 Early developments influencing G × E × M interactions in western Canada

1.3.1 The introduction of 'Marquis' hard red spring wheat – 1911

'Marquis' hard red spring wheat was the result of a cross between Red Fife and 'Hard Red Calcutta'. The cross was first made by Dr. A. P. Saunders, the son of the founder of the Dominion Experimental Farms program, Dr. William Saunders, and brother of Sir Charles Saunders (Morrison 1960, McCallum and DePauw 2008). Sir Charles Saunders selected and eventually released to growers the line to be named Marquis in a limited quantity in 1908 and then more broadly in 1911. Relative to Red Fife, Marquis exhibited earlier maturity, reduced height, reduced grain shattering and increased grain yield – all key requirements of a new successful wheat variety in western Canada and the northern United States (Newman 1928, Morrison 1960). Marquis quickly replaced Red Fife as the dominant wheat variety grown in Canada accounting for 90% of spring wheat plantings and 60-70% of spring wheat plantings in the northern United States by as early as 1920 (Newman 1928, McCallum and Depauw 2008). The popularity of Marquis through this period made it the model variety for early agronomic studies in Canada, primarily taking place at the Dominion Experimental Farms. McKillican (1924) reported on one such experiment where Marquis wheat was planted at Brandon, Manitoba each year from 1917-1923 and evaluated for stem rust (*Pucinnia graminis*) infection. The results of this study indicated earlier plantings, greater planting rates, and planting on fallow rather than immediately after another cereal crop reduced stem rust severity. Similarly, Conners (1925) reported on the control of bunt (*Tilletia tritici* and *Tilletia levis*) in Marquis wheat using several chemical control methods. Early agronomic studies such as these focused on improving the management of wheat growing systems in western Canada and were made possible by the broad suitability of Marquis wheat for production and use in the region.

1.3.2 Regional wheat variety acceptance

Marquis remained the primary wheat cultivar grown in western Canada until 1939 when it was surpassed by ‘Thatcher’ (Anonymous 1934, McCallum and DePauw 2008). However, the broad adaptability and improvements in agronomic quality over previous cultivars exhibited by Marquis did not provide the same level of benefit to all of the wheat growing regions of western Canada. Expansion of wheat production into more northern areas of Saskatchewan and Alberta, including the Peace River region, did not reliably allow the accumulation of a sufficient number of growing degree days for Marquis to reach maturity (Geddes et al. 1932). Frost damage that affected grain yield, grain quality and the resulting grain grade were common in the late 1920’s and early 1930’s (Geddes et al. 1932). Newer varieties were developed and gained acceptance in more localized regions. For example, the cultivar ‘Garnet’ was released in 1926, and while it required five to ten fewer days to reach maturity than Marquis, it produced a lower quality milling wheat (Newman and Whiteside 1927, Larmour 1931, Malloch et al. 1932, McCallum and DePauw 2008). For producers in the northern regions of western Canada, the benefit of Garnet’s consistently earlier maturity outweighed the cost of the lower milling grade. Increased focus on wheat breeding specifically for western Canada enabled regional cultivar selections and regional preferences to be based on predominant environmental conditions. The ability to sow cultivars with regional suitability had not been realistic prior to the increase in selection for western Canadian growing conditions, as one primary cultivar tended to dominate the region as a whole.

1.3.3 Mechanization of agriculture in western Canada

Wheat production in western Canada did not exist in a vacuum; the geopolitical upheaval caused by the first World War initiated significant changes in what had become the agricultural norm. The sale and adoption of tractors on farms in the northern Great Plains has been studied as a metric of mechanization (Ankli 1980, Lew 2000, Lew and Cater 2018). The internal combustion engine was introduced in the early twentieth century; however, cost, reliability, small farm size and low-cost labour slowed any significant early adoption on the northern Great Plains (Lew and Cater, 2018). The onset of World War I imposed two distinct challenges for agriculture in western Canada: the requirement for greater production, and at the same time the loss of available labour. Tractors were not recorded on the censuses of the United States or Canada until 1920 and 1921 respectively (Lew and Cater 2018). Available reports indicate 1000 tractors on farms in the United States in 1910, and 5000 by 1915 (Carter et al. 2006). In Canada, 3000 tractors were reported on farms in 1910, and 15,000 by 1915 (Urquhart 1993). However, the validity of the Canadian numbers from Urquhart (1993) is disputed by Lew and Cater (2018) as the report likely groups stationary engines as tractors. Regardless of the reported numbers, the trend is an increase in adoption of tractors from 1910-1915 and from 1915-1920. Tractors were adopted on 10-20% of farms by 1920 across the Canadian prairie provinces and northern United States, depending on the state or province.

Mechanization on the northern Great Plains between 1915 and 1930 was driven by reduced labour availability during World War I, larger average farm sizes relative to eastern Canada or the eastern United States, time sensitive farm operations such as harvest prior to wheat shatter, improved efficiency versus horse drawn equipment, and relatively strong farm prosperity during the period (Hopkins et al. 1932, Sargen 1979, Clarke 1994, Lew 2000, Lew and Cater 2018). At the onset of the Great Depression, adoption of tractors in western Canada slowed relative to the northern United States. This was in part due to the poor growing conditions that defined the era, but additionally the abundance of labour brought on by significant differences in immigration policies between the countries at the time (Lew and Cater 2018). The availability of labour resulted in lower wage expectations in Canada; when combined with the relatively higher cost of tractors and equipment in Canada (due to Canada/United States tariffs), the speed of technology adoption in the region was reduced despite evident efficiency gains (Norrie 1974, Wylie 1989, Keay 2000, Lew and Cater 2018).

The onset of World War II increased demand for food production, reduced labour availability and quickly reversed the stagnation of technology adoption on western Canadian farms. From 1940 to 1945 Canadian farmers adopted technology at a rate equivalent to their United States counterparts, limited mainly by availability of machinery. From 1945 to 1950 tractor adoption on the Canadian prairies outpaced adoption in the northern United States such that by 1950 each region averaged about 0.8 tractors per farm (US Bureau of the Census 1961, Dominion Bureau of Statistics 1963, Lew and Cater 2018).

Increasing production and efficiency through technology adoption has continued in agriculture, driven by those adopting new technologies to receive the direct benefits of an innovation, and also by those induced to incorporate the technology by supply and demand market forces

(Chavas and Nauges 2020). Downing (1962) estimated cereal yields benefited 20-35% due to mechanization and the more efficient implementation of tillage, planting, fertilizer application and timely harvests. The integration of technology into on-farm management tactics provides both transformational and incremental change starting with the use of horse drawn equipment, transformed by mechanization and incrementally improved by precision and systemic understanding (Kirkegaard 2019, Beres et al. 2020).

1.3.4 Discovery of the Haber-Bosch process

Concurrently with the expansion of wheat breeding programs focused on western Canada, and the mechanization of agriculture in western Canada, the discovery of the Haber-Bosch process allowed industrial synthesis of ammonia from atmospheric nitrogen and enabled the introduction of synthetic nitrogen to crop management systems (Udvardi et al. 2021). The availability of synthetic nitrogen fertilizer shifted agriculture on the Canadian prairies from an endeavour limited by available soil nitrogen to one that removed this limiting factor and led to greater productivity (O'Neill et al. 2004). Previous to the discovery and industrialization of the Haber-Bosch process, cropping systems in western Canada were primarily reliant on existing soil nitrogen accumulated from the decomposition of roots and plant material from the rich grasslands that covered the area prior to settlement (Pennock et al. 2011). Continuous cropping primarily with cereals reduced the availability of nitrogen, degraded soil structure and compounded the effects of the drought experienced through the 1930's (McLeman and Ploeger 2012). Conventional knowledge of the period from 1930 to 2010 now indicate that of the nitrogen used by cereal crops, less than 50% is successfully accessed from applications of synthetic fertilizer the year of planting (Allison, 1955, Cassman et al. 2002, Tonitto et al. 2006, Gardner and Drinkwater 2009, Udvardi et al. 2021). The remaining percentage is made up by synthetic nitrogen applied in previous years, and from the same elements relied on by early settlers – mineralization from soil organic matter and crop residues (Olson et al. 1979, Jayasundara et al. 2007, Udvardi et al. 2021). The removal of material from the system in the form of grains or biomass necessitates the addition of nitrogen to the system either in the form of nitrogen fertilizer or through other tactics such as the cultivation of nitrogen fixing crops or green manures (Corbeels et al. 1999, Salvagotti et al. 2008).

Modern cropping systems on the Canadian prairies maintain a heavy reliance on synthetic nitrogen in order to maintain production and avoid the depletion of organic soil nitrogen (Tenorio et al. 2020). Roy et al. (2004) reported that synthetic nitrogen via the Haber-Bosch process accounted for 50% of the world's inorganic nitrogen production in 1931, 80% by 1950, greater than 90% by 1962 and 99% by the latter part of the 1990's. Similarly, Smil (1999) reported that 50% of corn growing systems in the United States relied on inorganic nitrogen additions in 1950, expanding to 99% by 1999. Global use of inorganic nitrogen rose sharply after World War II owing to increased wartime production and therefore increased capacity to supply agricultural uses after the war (Roy et al. 2004). Brown (1999) estimates 40% of the grain yield increases since 1960 are directly attributable to the proliferation of synthetic nitrogen fertilizer. Increased availability and use of nitrogen fertilizer partially enabled the grain yield gains realized through the genetic advancements initiated during the Green Revolution (Duvick and Cassman 1999, Thomas and Graf 2014).

1.4 The Green Revolution

The Green Revolution was a period of significant growth in global agricultural output driven mainly by increases in realized grain yields of wheat, rice and maize (Pingali, 2012). The duration of the Green Revolution, commonly described as the period between 1960 and 2000, included the tripling of cereal crop production volume and a doubling of the human population (Trewavas 2001, Wik et al. 2008, Pingali 2012). The primary catalyst of the Green Revolution was the development of elite cereal germplasm and modern cereal varieties made publicly available through the work of the International Center for Wheat and Maize Improvement in Mexico (CIMMYT) and the International Rice Research Institute in the Philippines (IRRI) which are now a part of the Consultative Group for International Agricultural Research (CGIAR) (Evenson and Gollin 2003). Early initial gains in cereals were reported in wheat and rice due to the significant breeding effort already invested in these crops globally at the time, and the wide genetic resources already available (Evenson and Gollin 2003). Incorporating dwarfing, or height reduction genes, into elite lines significantly benefited grain yield potential of new varieties. Dwarfing genes such as *reduced height* (*Rht*) genes in wheat and the *semidwarf1* (*sd1*) gene in rice reduced the length and increased the strength of the respective cereal's stems (Hedden 2002). A reduction in height and increase in straw strength reduced lodging and allowed higher yielding lines to remain erect past physiologic maturity. Additionally, reduced height allowed the repartitioning of photosynthate from vegetative growth at elongation into additional grain production (Hedden 2002). Peng et al. (1999) and Hooley (1994) reported that *Rht* genes in wheat functioned by interfering with the signal transduction pathway of gibberellin leading to the repartitioning of energy and carbohydrate within the plant. Plant height reduction and redistribution of photosynthate were the key discoveries of the Green Revolution that drove increases in grain yield, and potential grain yield, by improving harvest index values.

Genetic advances of the Green Revolution were successfully incorporated into Canadian wheat varieties, however, integration into commercial lines required significant time and effort due to poor agronomic characteristics associated with some *Rht* genes including stem rust, leaf rust, and fusarium head blight susceptibility, reduced coleoptile length and poor seedling vigour, shriveled kernels, and reduced grain quality (Dalrymple 1980, Schillinger et al. 1998, Ellis et al. 2004, Srinivasachary et al. 2009, Lumpkin 2015). Once successfully integrated with elite Canadian germplasm which allowed the retention of important agronomic and grain quality traits, the genetic advancements of the Green Revolution became part of the wheat growing system in western Canada and were paired with recent management advancements including increased fertilizer and pesticide use. The interaction of Green Revolution genetics and modern management practices resulted in grain yield and potential grain yield growth that outpaced population growth in the later part of the twentieth century (Dalrymple 1986, Hedden 2003, Evenson and Gollin 2003). Thomas and Graf (2014), Hucl et al. (2015), and Iqbal et al. (2016) reviewed the rates of grain yield increase, and grain yield increase from genetic improvement, across multiple Canadian wheat varieties and classes in the twentieth century. Iqbal et al. (2016) reported that genetic improvements of Canada Western Red Spring wheat varieties increased grain yield at a rate of 0.28% year^{-1} from 1885 to 2012, while Thomas and Graf (2014) reported grain yield increases driven by genetic improvements were 0.33% year^{-1} from 1972 to 1990 and 0.7% year^{-1} from 1990 to 2013. Additionally, Thomas and Graf (2014) reported the realized on-farm yields from 1991 to 2013 in the province of Manitoba increased by of 1.4% year^{-1} from 1991 to 2013. Therefore, in the absence of data regarding synergism between genetics and management practices, the realized on-farm grain yield increase of 1.4% year^{-1} reported by Thomas and Graf (2014) from 1991 to 2013 may be attributed equally to genetic gain, reported at 0.7% year^{-1}, and management improvement over the period resulting in the remaining 0.7%

$year^{-1}$ total grain yield increase. Yield gain resulting from improvements in both genetic potential and management tactics in this period mirror the methods by which grain yield gains were achieved during the Green Revolution.

1.5 Modern Canadian hexaploid spring wheat planting dates and rates

1.5.1 Optimum wheat planting date

Traditional wheat planting dates in western Canada endeavour to strike a balance between planting early enough to avoid freezing temperatures late in the season, and planting late enough to ensure final spring frosts do not cause substantial seedling mortality. Early settlers planting wheat cultivars requiring long periods to reach maturity often suffered from one of these extremes (McCallum and Depauw 2008). Present day wheat production on the Canadian prairies remains limited by short frost-free periods which have been addressed with breeding efforts to develop high-yielding early maturing varieties (Iqbal et al. 2006, Iqbal et al. 2007). In addition to breeding programs concentrating on early maturity, the frost-free period in western Canada has increased in length. Cutforth et al. (2004) reported that the average frost-free period in western Canada had increased from 96 days in 1940 to 114 days in 2000. Similar reports by Berry (1991), Skinner and Gullet (1993), Gan (1998), Cutforth (2000) and Zhang (2000) conclude the Canadian prairies are recording increasingly warmer average winter minimum temperatures and summer maximum temperatures from 1950 to 1989. Greater frost-free periods increase the amount of growing degree days available to be captured by wheat on the Canadian prairies and can potentially increase grain yield. Lanning et al. (2010) reported that the yield of the spring wheat variety Thatcher had increased over a 56 year period as a result of increased growing season length and the ability to successfully plant earlier in the season. Over the 56 year period the grain yield of Thatcher increased by 23.5 kg ha^{-1} $year^{-1}$ and the average planting time moved earlier by 0.24 days $year^{-1}$ (Lanning et al. 2010).

Multiple studies have evaluated planting dates using pre and post-Green Revolution wheat varieties (Larter et al. 1971, Briggs and Aytenfisu 1979, Ciha 1983, McKenzie et al. 2008, McKenzie et al. 2011, Lanning et al. 2012). Collectively these studies have reported that the earliest planting times evaluated resulted in either the greatest grain yield, grain yield not significantly different from later planting times, or grain yield greater than the later planting times and equivalent to median planting times. Similar results have been reported in other wheat growing regions including Australia and the Pacific Northwest region of the United States where earlier planting times improved or had no negative effect on grain yield (Batten and Khan 1987, Coventry et al. 1993, Gomez-Macpherson and Richards 1995, Kirkegaard et al. 2015, Hunt et al. 2018, Cann et al. 2020, Porker et al. 2020). Increased grain yield reported by Kirkegaard et al. (2015) and Hunt et al. (2018) was attributed to better plant establishment, longer vegetative growth periods and lower temperatures during flowering and grain fill for earlier planted wheat.

Despite the body of literature reporting improved yields from early planting of wheat, traditional crop insurance systems in western Canada provide only a single date by which wheat must be planted in order to qualify for grain yield and grain quality insurance coverage. The Agriculture Financial Services Corporation (AFSC), a major provider of crop insurance in western Canada, recommends wheat planting by May 31 of each year in order to maintain grain quality and yield potential; to date no incentive is provided for earlier plantings (AFSC 2022).

1.5.2 Optimum wheat planting rate

Grain yield curves for cereal planting rates tend to follow a parabolic trend where an optimum planting rate results in the greatest grain yield, and planting rates higher or lower than this optimum will result in reduced yield (Faris and Depauw 1980, Collier et al. 2013). Faris and Depauw (1980) evaluated three cultivars and six planting rates from 75 seeds m^{-2} to 1350 seeds m^{-2} over two years and reported that grain yield followed an expected parabolic yield curve with planting rates. However, Faris and Depauw (1980) identified a different optimum planting rate for each cultivar, correlated to the yield potential of each variety. Cultivars in the study with greater overall grain yield and greater overall grain yield potential reached maximum yield at higher planting rates. Of the three lines evaluated in this study, optimum yield was determined to be at 675, 486, or 350 seeds m^{-2}. The report concluded that new wheat cultivars should be tested at multiple planting rates in order to determine the appropriate optimum planting rate. Several studies completed with more recently released cultivars have determined that the positive grain yield effect of higher seeding rates was not cultivar specific, with some indicating that optimum planting rates may be variable between wheat classes (Lafond 1994, Lemerle et al. 2004, O'Donovan et al. 2005, Mason et al. 2007, Beres et al. 2011). Higher planting rate recommendations for modern higher yield-potential cultivars is in contrast with historical reports such as that of Woodward (1956), who reported no yield benefit in barley at planting rates beyond 30 to 40 pounds of seed acre^{-1} (33.6 to 44.8 kg ha^{-1}) and optimal wheat planting rates of 50 to 60 pounds of seed acre^{-1} (56.0 to 67.2 kg ha^{-1}), and Larter et al. (1971) who reported a negative grain yield effect when planting wheat at rates over 50 kg ha^{-1}. Higher planting rates are commonly recommended in studies evaluating wheat's competitive ability with weeds, yield stability challenges from pest pressure, and optimum management systems (Mason et al 2007, McKenzie et al. 2008, Beres et al. 2010, Beres et al. 2011, McKenzie et al. 2011, Harker et al. 2016).

Beres et al. (2011) previously reported on the effects of seeding rate on grain yield and on grain yield stability. In evaluations of three cultivars and one blend of two of the cultivars, planted at four different sowing densities, Beres et al. (2011) reported increased grain yield from the lowest to highest sowing density for all cultivar and blend treatments. The study then reported on the stability of grain yield as a metric of growing system stability, taking into account cultivar or blend, planting rate, and coefficient of variation. This method of stability analysis was originally proposed by Francis and Kannenberg (1978) as a grouping methodology to identify superior genotypes across multiple environments. Beres et al. (2011) applied the same grouping methodology using planting rate on the vertical axis and coefficient of variation on the horizontal access to assess grain yield, and thus, growing system stability relative to planting rate and cultivar (Figure 1-2). Beres et al. (2011) reported that grain yield was the lowest and least stable when sowing density was lowest; the two median sowing densities resulted in the greatest grain yield and grain yield stability. The highest planting density, despite high grain yields, began to negatively affect grain yield stability (Figure 1-2).

1.6 Potential effects of climate change on the wheat growing environment of western Canada

Wheat grain yield in western Canada is primarily limited by a short frost-free period (Cutforth et al. 2004, Iqbal et al. 2007). Despite the limited length of the growing season, the average wheat grain yield in western Canada has doubled from 1.5 MT to 3.0 MT hectare^{-1} from 1961-1970 to 2008-2017 (Statistics Canada 2021). The realized increase in grain yield over time in western Canada has been attributed to multiple factors including improved wheat genetics and agronomic management; rarely has the grain yield increase been attributed to increased growing season length (Cutforth et al. 2004, Lanning et al. 2010, Drury et al. 2014, Thomas and Graf 2014, Iqbal et al. 2016, He et al. 2018). The observed increase in growing season length within western Canada, due to earlier final spring frosts and later initial fall frosts, was subsequently accompanied by an increase in average growing season temperature. A continued increase in average growing season temperature has the potential to negate the beneficial effect of increased growing season length on grain yield (Asseng et al. 2004, He et al. 2012, Asseng et al. 2019).

Asseng et al. (2004) reported that the effects of climate change would include increased atmospheric CO_2 concentrations, increased average air temperatures and increased drought conditions resulting from decreases in overall rainfall, and changes in distribution of rainfall throughout the growing season to fewer more intense precipitation events (Jones 1996, Whetton 2001). While increases in atmospheric CO_2 have been shown to potentially increase grain yield, higher daily average temperatures and reduced water availability have been shown to reduce wheat grain yield (Kimball et al. 1995, Sayre et al. 1997, Turner 1997, Asseng et al. 2004). Asseng et al. (2004) developed a series of models to evaluate the effect of climate change on global wheat crop growth when increased atmospheric CO_2, water availability, increased air temperatures, and nitrogen availability were taken into account. The report of Asseng et al. (2004) indicated that when temperature increased and water availability decreased, wheat grain yield subsequently decreased, as well as the magnitude of the grain yield response to nitrogen fertilization, regardless of atmospheric CO_2 concentration. However, only a small yield decline was reported when high nitrogen rates were included in the system in conjunction with increased air temperature and decreased water supply at any evaluated CO_2 concentration. Increases in atmospheric CO_2 had a positive impact on grain yield when nitrogen was not limited.

Asseng et al. (2015) completed a similar study on the global impact of temperature increases on wheat production using an ensemble of 30 separate wheat cropping models in an effort to accurately simulate global wheat yield responses to rising temperatures. The ensemble of models was applied to 30 global locations using known baseline climate data at the sites from 1981-2010. Asseng et al. (2015) reported that the model ensemble more accurately reflected actual conditions and responses than any single model included in the ensemble. The model indicated 20 of the 30 locations in the study experienced grain yield decreases from 1981-2010 resulting from actual temperature increases observed over the period. In two scenarios, with average daily temperature increases of 2°C and 4°C applied to the model ensemble, grain yield declines ranged from 1% to 28% and 6% to 55% respectively across all locations (Figure 1-3) (Asseng et al. 2015). Canada was represented in the model by a location in Lethbridge, Alberta which indicated a grain yield increase from 1981-2010 with actual climate data, minimal grain yield reduction with a 2°C increase in average daily temperature (-1%) and a moderate decrease in grain yield with a 4°C increase in average daily temperatures (-12% to -16%) (Figure 1-3). The study indicated the decrease in grain yield predicted by the model ensemble due to increasing temperature was primarily a result of a shorter growing season, limited by heat and a resulting reduction in the number of kernels produced per unit area. Grain size and harvest index in the models remained largely unchanged. Asseng et al. (2015) concluded that changes in temperature alone, in the absence of other climate change effects, had the potential to significantly decrease global wheat yield, which supported the results of several previous studies that had evaluated temperature in combination with other factors (Asseng et al. 2011, Ottman et al. 2012, Pradhan et al. 2012).

Qian et al. (2019) published an initial comprehensive evaluation of the impacts of climate change on the production of major crops in Canada. The study used three separate crop models and an ensemble of 20 Global Climate Models to evaluate crop production of wheat, canola, and maize in 55 different Canadian Regional Agricultural Model regions. The study used a baseline global average temperature from 1850-1900 as calculated within each Global Climate Model and then evaluated crop production in each crop model with an increase of 1.5°C, 2.0°C, 2.5°C, or 3.0°C from the baseline. Crop production was evaluated for a 30-year period with the median year being the year that the targeted temperature increase was reached. Qian et al. (2019) reported "significant spread" in resulting yield change across the 20 Global Climate Models used in this study and, similar to Asseng et al. (2015), reported the use of an ensemble of models created a more reliable result that any models used alone. Yield changes reported for the Canadian Regional Agricultural Model regions were reported as a percentage change from the average actual crop production for each crop in the region from 2006-2015. Each crop model employed, (the Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al. 2003), DeNitrification DeComposition (DNDC) (Li 2000), and Daily CENTURY Model (DayCent) (Parton et al. 1998, Del Grosso et al. 2001)) modeled similar important processes. Differences in the processes included in each model account for variances in output between them, resulting in directional but not identical results between models. The processes captured in each model are provided in Table 1-2.

Figure 1-4 presents the expected yield change in Canada of wheat, canola and maize based on the 20 Global Climate Models, and three crop models previously described. Average wheat and canola yields tended to increase in all three models at all levels of temperature increase investigated, however the consistency of grain yield tended to decrease, as exhibited by wider spread between the 25th and 75th percentiles at the higher temperature increases in Figure 1-4. Average grain yield of maize tended to remain similar, but decreased in consistency with increasing average temperature in 2 of 3 models. In the DNDC model, maize yield increased. The main reason for the differential response between wheat and canola compared to maize was reported in the study as a predicted increase in precipitation in the areas commonly growing wheat and canola relative to the maize growing regions of Canada, and the ability of C_3 plants to take advantage of increased CO_2 concentrations. Hatfield et al. (2011) previously reported C_3 plants could exhibit increases in grain yield production by as much as 30% if CO_2 concentration in the atmosphere was to double, while Leakey et al. (2006) reported little to no positive effect of increased atmospheric CO_2 concentration on C_4 plants.

The ensemble models of Asseng et al. (2015) indicated a decrease in global wheat production as global average temperatures continued to rise, however, Canada was only represented by one location in the study, and had a reduced negative response relative to locations closer to the equator. This trend of reduced effect of temperature increases on grain yield in higher latitude northern and southern locations is presented clearly in Figure 1-3, with reduced grain yield losses. The regional work of Qian et al. (2019) indicated a potential positive effect of increased daily temperatures on wheat production in Canada. Adaptations recommended by Qian et al. (2019) included adoption of new varieties of current crops, and a shift to warmer season and longer season crops to potentially take advantage of greater average temperatures and longer growing seasons in western Canada. The possibly beneficial, although possibly temporary, effect of climate change on agriculture in western Canada has been reported in single model studies prior to the ensemble model-based report of Qian et al. (2019) (Wang et al. 2012, Smith et al. 2013, Qian et al. 2016, Qian et al. 2016a, He et al. 2018). Specifically, the report of Qian et al. (2016) evaluated a regional climate model with the DSSAT wheat crop model with seven climate change scenarios and two forcing scenarios including higher atmospheric CO_2 concentrations. Similar to the results reported in Qian et al. (2019) many locations exhibited greater wheat grain yield from 2041–2070 than from 1971– 2000. Locations farther south within Canada tended to have lower or negative grain yield gains relative to locations farther north. In addition, Qian et al. (2016) presented the average grain yields across all locations when spring planting occurred at a set date each year or was varied with environmental conditions similar to the methods of Bootsma and Dejong (1988). When planting date was adjusted to earlier in the season, increasing growing season length, the magnitude of the grain yield benefit increased. Qian et al. (2016) specifically report the caveat that the percentage yield increase presented in their study could be inherently flawed as crop models tend to underestimate the negative effect of heat stress, however the directional indication of yield increase with increased temperature, CO_2 concentration and precipitation remains valid.

Despite reports of global wheat grain decreases with average daily temperature increases resulting from climate change, Canada is one of the few large wheat producing countries in the world in a position to potentially benefit from increased temperatures and growing season length. Adaptation of the wheat growing system in Canada is required to take advantage of the potential benefits and avoid grain yield loss to potential increased heat and drought stress events. Several potentially beneficial management adaptations to wheat production systems in western Canada have been discussed, including: increasing growing system nitrogen supply under increased atmospheric CO_2 concentrations in order to capitalize on improved water use efficiency, adopting new varieties selected to take advantage of longer growing seasons and better tolerate higher temperatures, and adjusting planting dates to earlier in the season to avoid later season heat stress.

1.7 G × E × M interactions in wheat growing systems

Cropping systems are a combination of intertwined systems and tactics reliant on influencing or responding to the interactions of genotype (G) × environment (E) × management (M) (Beres et al. 2020a). The results of these interactions between G × E × M dictate the potential yield of a cropping system, which is the yield of the most adapted available cultivar when combined with optimal agronomic management practices, and no negative exertion of manageable abiotic or biotic stresses (Fischer 2015). Lobell et al. (2009) reported that 50% or more of global potential yield is not achieved in rain-fed growing systems, and 20% or more of potential yield is not realized in irrigated growing systems for the world's main crops, wheat, rice and maize. Much of the history of growing wheat in Canada, outside of political effects, has been a struggle to increase the potential yield and realized yield of the wheat growing system by implementing improvements in G and M in order to lessen the effect of, or take advantage of E.

Depending on the region, potential yield is limited by available water, growing season length, and economic constraints (Iqbal et al. 2016, Beres et al 2020a). Economic constraints specifically limit yield from the point where the cost of production of the next unit of yield results in a lower return than the previous unit of yield, thus the economic maximum yield does not equal the maximum potential yield of the growing system (Fischer 2014, Hatfield and Beres 2019, Beres et al. 2020a). Zhang et al. (2019) reported the economic yield of global cropping systems tends to be 75% to 85% of the actual potential yield of the systems. The gap between the realized on-farm yield and the economic maximum yield is considered to be the achievable yield gap, and can be narrowed through improved exploitation of G and M resources within E (Hochman and Horan 2018, Beres et al. 2020a). Similarly, new discoveries in G and M will raise the potential yield, or water limited yield, of a system, however, only if the discoveries are economically viable to be implemented in a growing system can they reduce the yield gap between on-farm yield and economic yield (Hochman and Horan 2018).

Hochman and Horan (2018) reported on the use of new management practices in the Australian wheat production regions. Early sowing was recommended as a best management practice and has been reported as a management tactic to increase wheat yield by multiple studies in Australia, especially when used in combination with later maturing wheat varieties (Kirkegaard and Hunt 2010, van Rees et al. 2014, Hunt et al. 2018). Hochman and Horan (2018) additionally reported that the benefit of earlier seeding dates and longer season genetics was increased when more nitrogen fertilizer was used in the system. This is an example of a new management tactic (early planting) and a new genetic advancement (later maturing varieties) being complemented by adjusting a current management tactic (increasing nitrogen fertilization). The new planting date and the new wheat varieties would extend the potential water limited yield, while the addition of extra nitrogen closes the gap with the on-farm potential yield.

Managing and reducing yield gaps requires optimal management of G and M to maximize the return, or minimize the damage of the least controllable variable, E. Lobell et al. (2009) and Ray et al. (2015) reported a major constraint on global crop production was weather or climate. Multiple studies have concluded the availability of moisture was a key limiting factor for any potential growing system adaptations (Mueller et al. 2012, Sinclair and Rufty 2012).

Systems-type approaches have been reported to improve grain yield and stability when focused on the interactions of G, E and M. Kirkegaard and Hunt (2010) utilized a systems-based approach to successfully manage wheat genetics, variation in environmental conditions, and agronomic management practices in a wheat production system. By optimizing management and genetics for the environment the system resulted in a nearly three-fold increase in yield potential, and an increase in the overall growing system stability (consistency of grain yield). The study reported by Kirkegaard and Hunt (2010) exhibited a system benefit greater than the summed benefit of any of the individual system manipulations. This indicated the presence of synergism when optimal management of G × E × M interactions is achieved. Growing systems that have been built on sound analysis of G × E × M interactions and are designed to take advantage of synergies between growing system components may maintain greater yields under adverse environmental conditions, and increase potential and realized grain yield and grain yield stability when environmental conditions are favourable (Fischer and Conner 2018, Beres et al. 2020, Cassman and Grassini, 2020).

Continuous advances in wheat genetics and crop system management technology are required in order to achieve the required expansion in crop production and reduction in resource use intensity necessary to achieve 3 billion MT of cereal grain production per year by 2050 (Alexandros and Bruinsma, 2012). Discovering and expanding growing system synergies in order to fully exploit G × E × M interactions increases the efficiency of global crop production and can drive rapid increases in realized on-farm yield and yield stability, while helping to maintain grain yield stability in regions negatively impacted by climate change (Beres et al. 2020, Beres et al. 2020a, Porker et al. 2020, Hatfield and Beres 2019, Kirkegaard 2019, Hunt et al. 2018, Kirkegaard and Hunt 2010).

1.8 Summary

Spring wheat (*Triticum aestivum* L.) is currently and historically one of the most important crops sown on the northern Great Plains of Canada, and was directly tied to the settlement and growth of the region. Canada is the world's sixth largest producer of wheat (32.3 M MT in 2019) and third largest exporter of wheat (22.8 M MT in 2019), with a majority of production coming from spring growth habit hexaploid wheat grown in Alberta, Saskatchewan and Manitoba. Wheat production on the Canadian northern Great Plains expanded as a result of early farmers applying local knowledge and new technology to manage environmental conditions, and dedicated plant breeders and scientists working to develop cultivars and management tactics suitable for production in the harsh, short season climate. Technology advanced and, though the term was not used, G × E × M interactions were harnessed to increase wheat production and increase the prosperity of the region and country as a whole. The success of wheat on the Canadian northern Great Plains is important to the globe, as Canada emerged as an integral exporter of wheat in order to feed a growing world. Mechanization, nitrogen fertilizer and the Green Revolution accelerated growth in production. Wheat production continues to have challenges and opportunities in Canada - rising global temperatures are a challenge for global wheat production and both a challenge and opportunity for Canada. Rising temperatures may lead to greater potential wheat yields in Canada, but also come with the need for greater production to account for regions of the world where temperature increases will decrease grain yield. A focus on increased wheat production in Canada is required to avoid the destabilizing effects hunger repeatedly causes in the world. In isolation, current genetic gain, yield potential, and technology advancements may not be able to generate an additional one billion MT of global cereal grain production by 2050. Significant focus on wholistically managing growing systems to fully exploit the synergy of optimized G × E × M interactions and avoid climate related yield decreases are paramount to wheat production in Canada in the next 30 years.

1.9 Tables

Table 1-1: Comparative areas and yields of wheat in the Northwest Provinces 1900 to 1911.

Wheat Production	**1900**	**1906**	**1908**	**1909**	**1910**	**1911**
Northwest Provinces Total						
Hectares	1,010,310	2,049,592	2,276,923	2,784,615	3,398,947	3,883,765
MT	638,571	3,010,530	2,500,535	4,014,936	3,508,829	-
Average grain yield (MT ha^{-1})	0.632	1.469	1.098	1.442	1.032	-
Manitoba						
Hectares	795,624	1,101,651	1,197,165	1,136,842	1,220,405	1,304,858
MT	499,626	1,482,909	1,368,485	1,434,828	1,120,481	-
Average grain yield (MT ha^{-1})	0.628	1.346	1.143	1.262	0.918	-
Saskatchewan						
Hectares	197,235	857,281	970,040	1,491,903	1,962,753	2,314,130
MT	117,226	1,366,126	945,789	2,319,338	2,208,866	-
Average grain yield (MT ha^{-1})	0.594	1.594	0.975	1.555	1.125	-
Alberta						
Hectares	17,451	90,660	109,717	155,870	215,789	264,412
MT	21,720	161,495	186,261	260,771	179,483	-
Average grain yield (MT ha^{-1})	1.245	1.781	1.698	1.327	0.832	-

From Bishop (1912), reproduced by G. Collier.

Table 1-2. Major model processes for crop simulation in the Decision Support System for Agrotechnology Transfer (DSSAT), the DeNitrification DeComposition model (DNDC) and the Daily CENTURY model (DayCent).

	Crop Models		
Model Processes	DSSAT	DNDC	DayCent
Crop development			
Cumulative heat (thermal time)	Yes	Yes	Yes
Impacted by water and nutrient stress	Yes	No	Yes
Harvest triggered by maturity	Yes	Yes	Yes
Cultivar explicit parameterization	Yes	Yes	Yes
Crop growth rate			
Function of photosynthesis/respiration	Yes[α]	No	No
Function of radiation use efficiency	Yes[β]	Yes	Yes
Impacted by water and nutrient stress	Yes	Yes	Yes
Temperature response curve	Yes	Yes	Yes
Stage dependent temperature stress	No	Yes	No
Stage dependent water stress	No	Yes	Yes
Crop response to atmospheric CO_2			
Photosynthetic carbon assimilation rate	Yes	Yes	Yes
Transpiration rate	Yes	Yes	Yes
Nitrogen use	Yes	Yes	Yes
Major model frameworks			
Cascade water flow	Yes	Yes	Yes[c]
Water demand a function of potential evapotranspiration	Yes	Yes	Yes
Layered nitrogen movement	Yes	Yes	Yes
Heterogeneous soil characterization	Yes	No	Yes

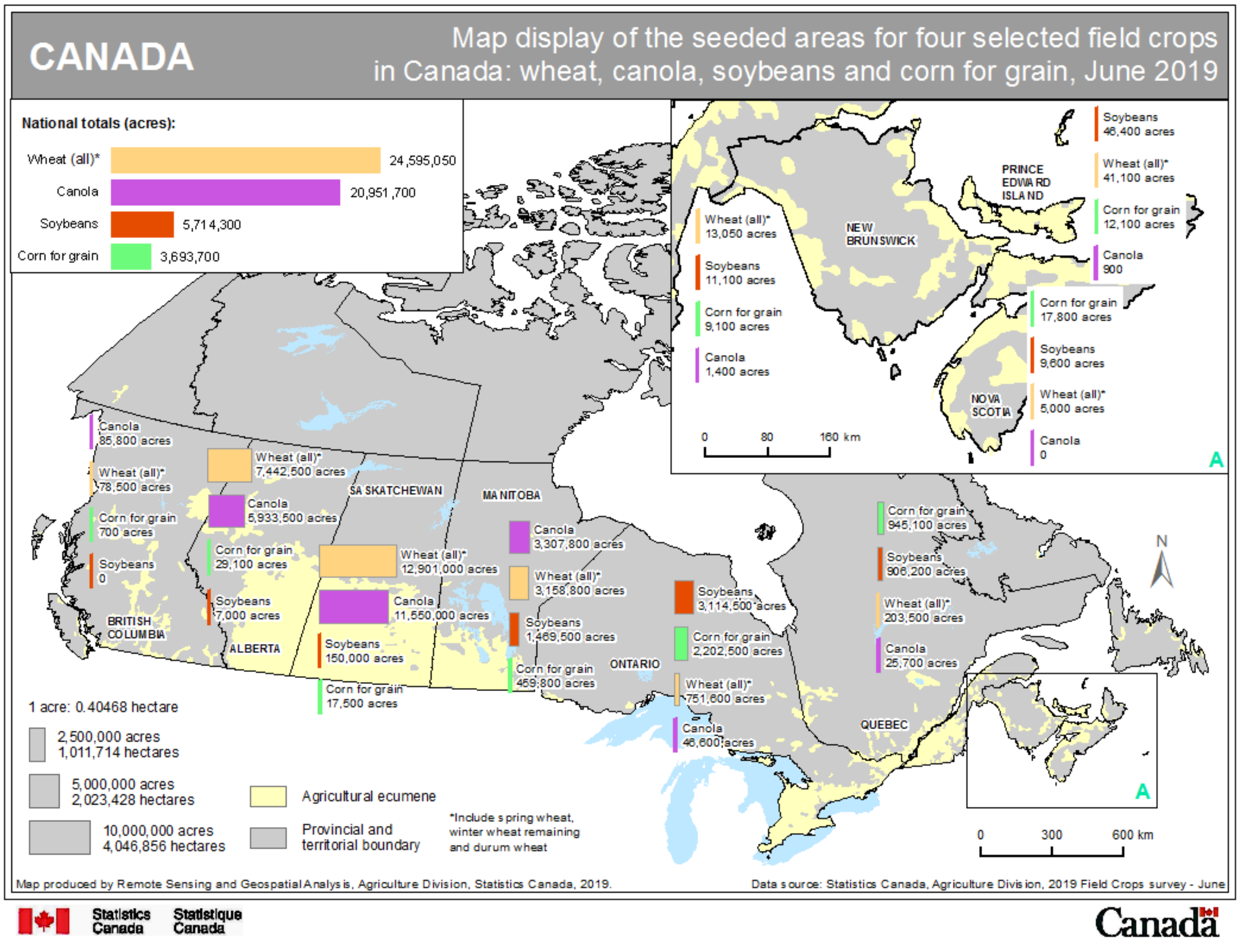
[α] The CSM-CROPGRO-Canola model uses the function of photosynthesis

[β] The CSM-CERES-Maize model and the CSM-CERES-Wheat model use the function of radiation use efficiency

[c] Unsaturated flow also occurs below field capacity.

From Qian et al. (2019), reproduced by G. Collier.

1.10 Figures



https://www150.statcan.gc.ca/n1/daily-quotidien/190626/mc-b003-eng.htm

Figure 1-1. From Statistics Canada (2021). Planted area in Canada by primary crop, June, 2019.

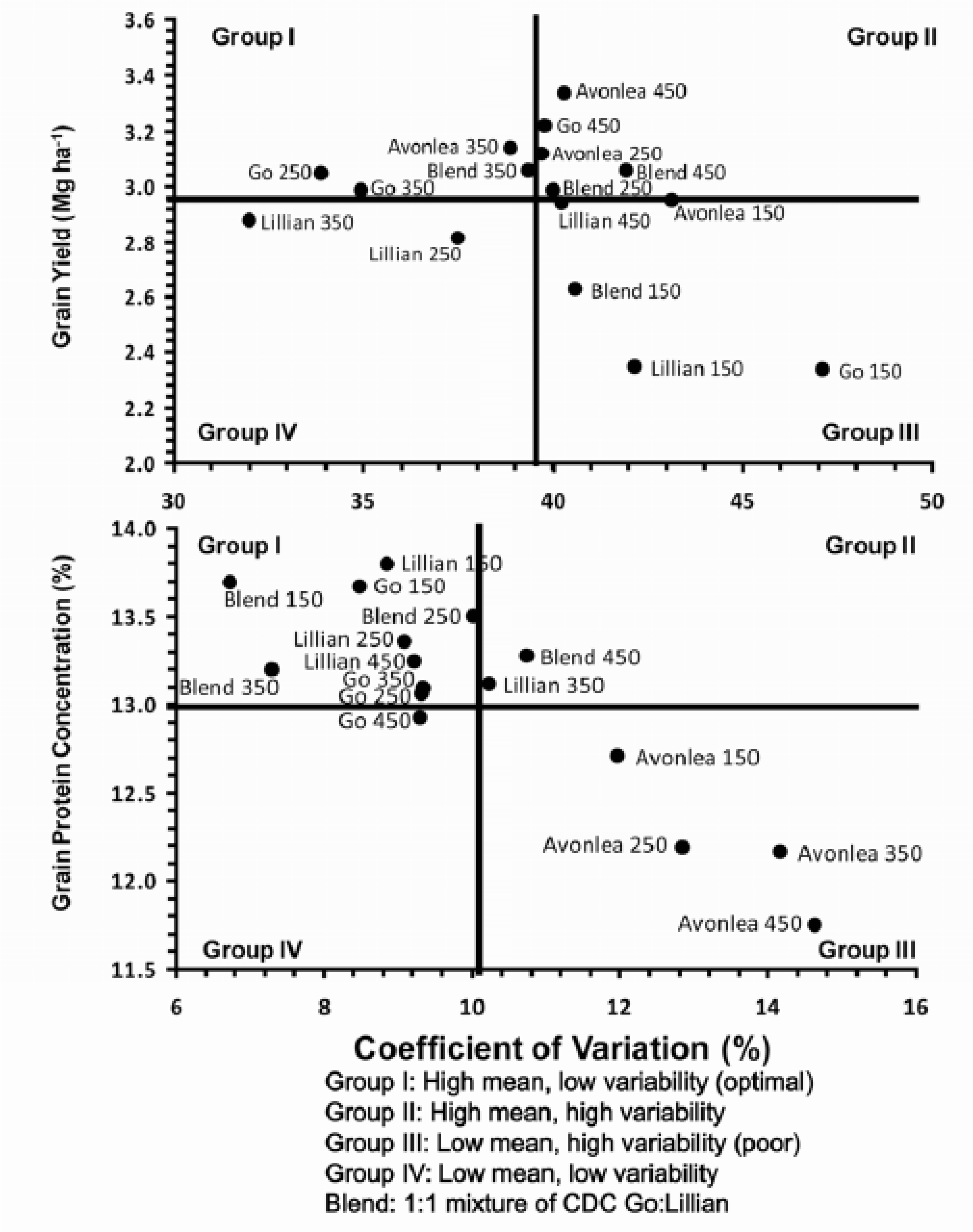


Figure 4-7. **Biplot (mean vs. CV) of variety and sowing density combinations for grain yield and protein concentration data collected at Coalhurst and Nobleford, Alberta, Canada, 2006–2009. The prefix of the labels indicates the variety selected followed by the planting density (150, 250, 350, or 450 seeds m^{-2}).**

Figure 1-2. From Beres et al. (2011). An example of a bi-plot using the bi-plot grouping methodology adapted from Francis and Kannenberg (1978) to represent grain yield and growing system stability in response to changes in sowing density and cultivar/blend.

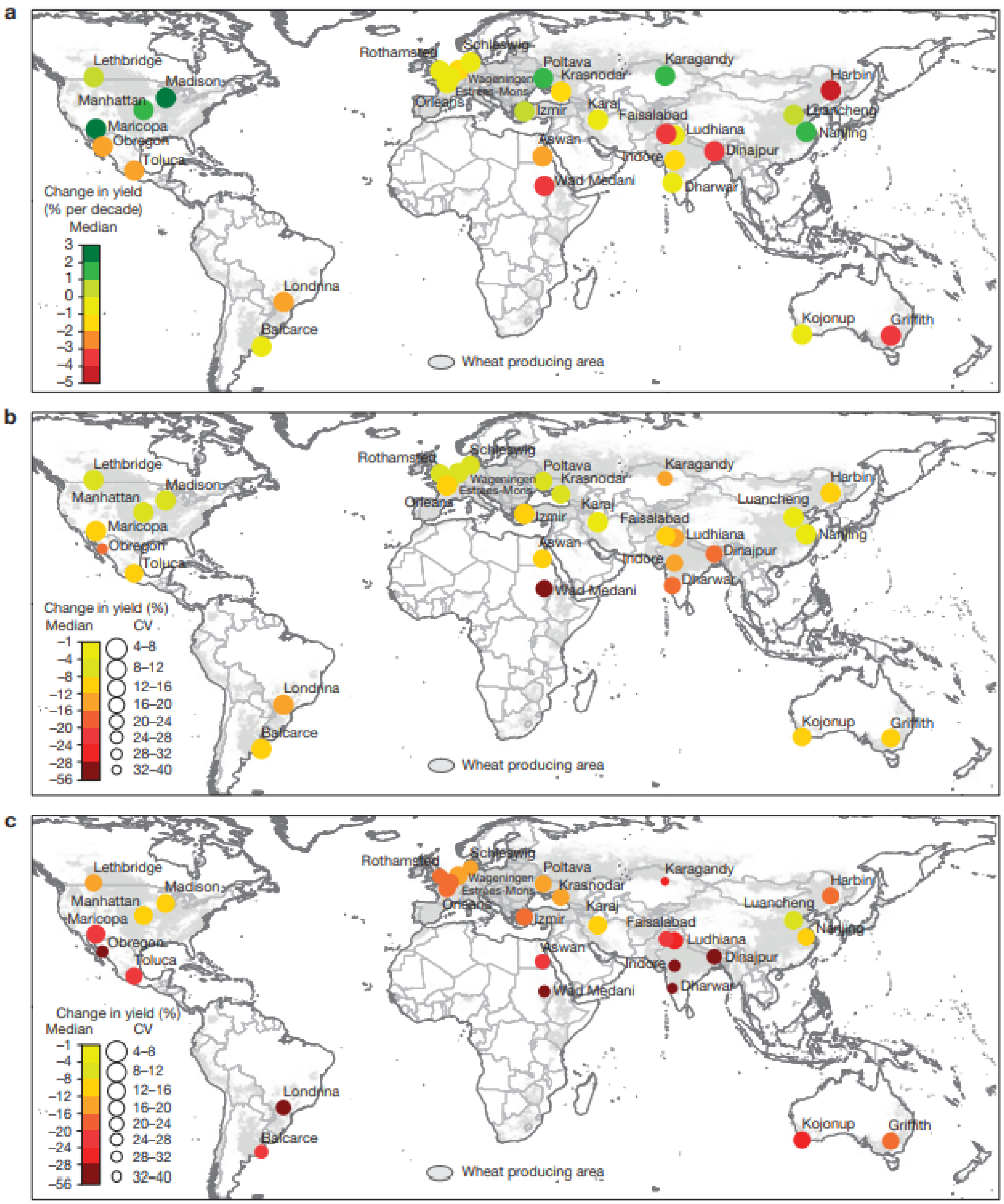


Figure 1-3. From Asseng et al. (2015). Simulated global wheat grain yield changes in the past and with forced temperature increases. **a**) Grain yield trends for 1981-2010 based on the median yield of a 30-model ensemble. **b,c**) Relative median grain yield for +2°C (**b**) and +4°C (**c**) temperature increases imposed on the 1981-2010 period for the 30-model ensemble using region-specific cultivars. Simulation model uncertainty was calculated as the coefficient of variation (CV%) across 30 models and plotted as circle size. The larger the circle, the less uncertainty. Impact on grain yield of average daily temperature change at 30 locations over time resulting from an ensemble model of thirty separate wheat cropping models.

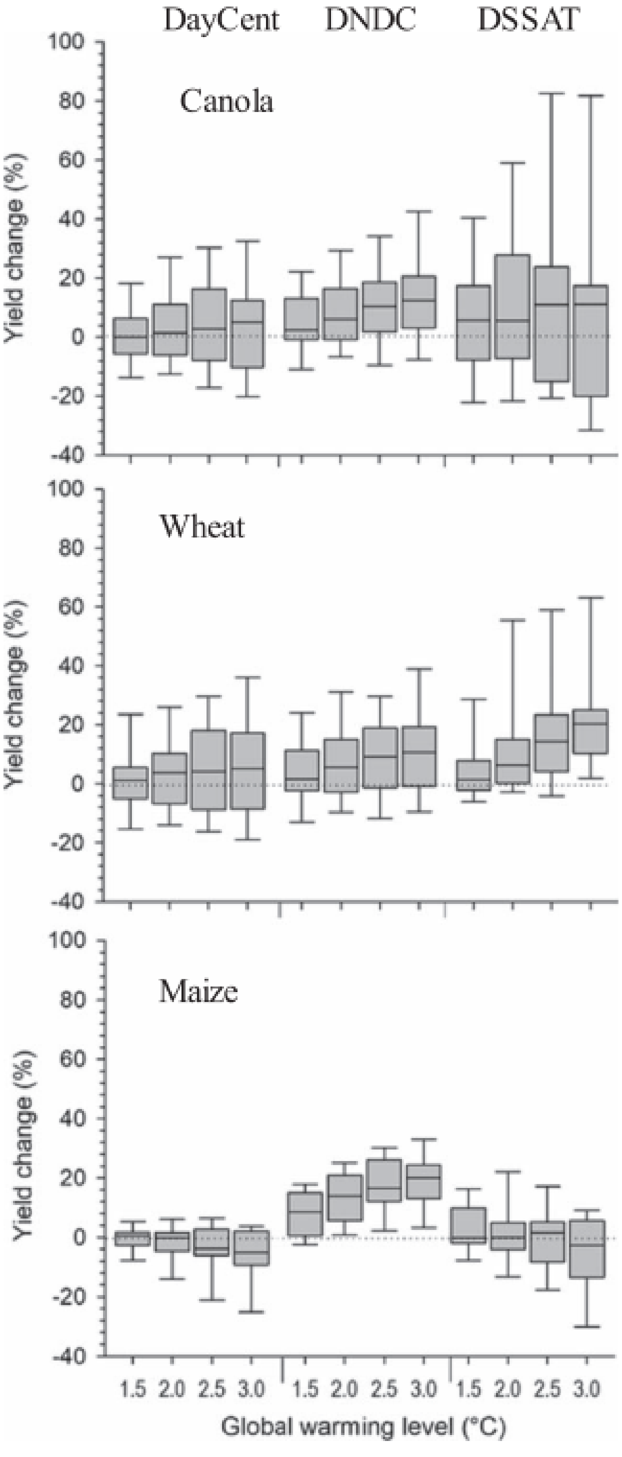


Figure 1-4. From Qian et al. (2019). Projected changes, relative to the baseline climate of 2006–2015, in the simulated crop production under water-limited (rainfed) conditions for canola, wheat and maize in Canada under the global warming levels of 1.5 °C, 2.0 °C, 2.5 °C, and 3.0 °C, by crop simulation models Daily CENTURY (DayCent), DeNitrification DeComposition (DNDC) and the Decision Support System for Agrotechnology Transfer (DSSAT). The boxplots show the 10th, 25th, 50th, 75th, and 90th percentiles of projected changes across the 20 GCMs.

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1.12 How this Ph.D. program arose

I completed a M.Sc. at the University of Alberta in 2012 and after considering entrance into a Ph.D. program, I instead returned to a position in the agriculture industry managing a research farm in central Alberta. In 2015 the opportunity arose for me to move to a new position within the industry and concurrently start a Ph.D. program. At that time Dr. Brian Beres at Agriculture and Agri-Food Canada– Lethbridge, a former graduate student of my M.Sc. supervisor Dr. Dean Spaner at the University of Alberta, was set to begin a project evaluating early spring wheat planting based on soil temperatures. Dr. Spaner and Dr. Beres were kind enough to take me on as a graduate student despite my full-time commitment to my career, as well as my commitments to my family and our farm.

The initial concept for early planting was borne of previous seeding date studies and an observation made by Dr. Beres in Montana, USA. Previous studies primarily relied on calendar dates for planting triggers, which poorly correlated to actual growing conditions from year to year. While in Montana, Dr. Beres noted that producers were planting spring wheat much earlier than their counterparts directly across the border in Canada. This observation brought about the question – how early can we plant spring wheat before we see a negative impact on grain yield production? This question was the foundation of the studies included in this thesis. As challenges and opportunities were considered, new questions arose about managing the harsh environment with specialized genetics, optimizing agronomic management practices and the potential benefits of an early planting system in the face of increasing global temperatures. These questions resulted in the research described in this thesis and the subsequent ultra-early wheat growing system presented.

1.13 Contributions to this thesis

Graham Collier – managed implementation of the studies reported in chapters two, three, four and five. Conceptualized hypotheses and field experiments reported in chapters four and five, managed all research activities for trials at the Edmonton location, prepared all experimental materials for Edmonton location and for all locations for studies reported in chapters four and five. Performed data analyses and was primary author of all manuscripts.

Dr. Dean Spaner – Co-Supervisor. Mentored me through my time in the program, including an independent study program in plant breeding. Supported me at the Edmonton location and helped motivate me to complete this thesis. Mentored manuscript preparation and statistical analyses, and edited all manuscripts.

Dr. Brian Beres – Co-Supervisor. Provided advice and support throughout the projects. Conceptualized hypotheses and field experiments reported in chapters two and three. Mentored manuscript preparation, statistical analyses and edited all manuscripts.

Dr. Robert Graf – Provided advice, developed the cold tolerant wheat lines evaluated in chapters two, three, four and five. Reviewed and edited all manuscripts.

Dr. Linda Hall – Assisted in conceptualization of the study and editing of the manuscript presented in chapter five. Mentored me in an independent study focused on integrated weed management and herbicide resistance in *Kochia scoparia* L., and provided support throughout my program.

Dr. Miles Dyck – Kindly mentored me in an independent study course in soil fertility.

Dr. Rong-Cai Yang – Provided suggestions for statistical analyses in chapter three, and was a kind supporter throughout my program.

Ms. Cindy Gampe – Completed research activities at the Scott, Saskatchewan location, and provided a review of the manuscript in chapter four.

Mr. Craig Stevenson – Provided statistical analyses support for the manuscripts in chapters two and three.

Mrs. Erin Collier – contributed to editing this thesis and all manuscripts.

1.14 Hypotheses and objectives of this thesis

The main hypothesis of this thesis was to determine if spring wheat could be successfully planted earlier in the spring than was conventionally practiced, and if so, could a growing system be developed that would lead to improved grain yield and grain yield stability relative to current practices.

The specific objectives of this thesis were to:

1. Determine if conventional and/or cold tolerant spring wheat could be planted into soils as cold at 0°C without detrimental effects on grain yield or grain yield stability.
2. Determine if modifications to the agronomic components of an ultra-early spring wheat growing system could increase grain yield or grain yield stability.
3. Determine if adaptation of Canadian hexaploid spring wheat varieties to ultra-early growing systems is specific to individual varieties, or market classes.
4. Evaluate the crop-safety and growing system benefit of replacing spring pre-seed herbicide applications with fall-applied residual herbicides.
5. Design an ultra-early wheat growing system easily adoptable for western Canadian producers to increase current grain yields and increase the resiliency of wheat production in western Canada in response to climate change.

The null hypotheses tested were:

1. Canadian hexaploid spring wheat will not exhibit reduced grain yield when planted early into sub-optimal soil conditions.
2. Specialized cold tolerant spring wheat varieties will not be required to avoid reductions in grain yield or grain yield stability when planting occurs early into sub-optimal soil conditions.
3. Manipulations of agronomic growing system components will not result in increases in grain yield or grain yield stability when Canadian hexaploid wheat is planted early into sub-optimal soil conditions.

4. Tolerance of Canadian hexaploid spring wheat to early planting into sub-optimal soil conditions will not vary between Canadian wheat market classes or between commercial wheat varieties.
5. Fall-applied residual herbicides will not result in phytotoxicity when Canadian spring hexaploid wheat is planted early into sub-optimal soil conditions the following spring.
6. The grain yield and grain yield stability of an ultra-early wheat growing system on the northern Great plains will not be equal to the grain yield and grain yield stability achieved with current wheat growing systems.

2.0 The integration of spring and winter wheat genetics with agronomy for ultra-early planting into cold soils[1]

2.1 Introduction

Canada is a globally important producer and exporter of high-quality wheat. In 2016 Canada ranked as the world's fifth largest producer of wheat (32.1 MT), and third largest exporter (19.7 MT) (FAOSTAT 2019). Wheat production in the Northern Great Plains region of western Canada is limited by a short frost-free period which dictates the requirement for early maturing spring wheat varieties (Iqbal et al., 2007). Cutforth et al. (2004) calculated the average frost-free season in western Canada as 96 days in 1940, increasing to 114 days in 2000, a trend expected to continue. This increase in growing season length is one of many contributing factors accounting for increases in western Canadian spring wheat production from an average of 14.3 MT on 9.63 Mha from 1961 to 1970 to 19.8 MT on 6.63 Mha from 2008 to 2017 (Statistics Canada 2019). Growth of the frost-free period has occurred as a result of both earlier final spring frosts, and later initial fall frosts (Cutforth et al. 2004), the former being correlated to calendar date and used as the current primary determinant of seeding date in western Canada. Lanning et al. (2010) reported that grain yield of the variety ‘Thatcher' had increased over 56 years of comparative data and attributed this to earlier planting and longer growing seasons. However, increased average growing season temperatures that have accompanied longer frost-free periods have the potential to reduce yield due to higher temperatures during grain fill and reduced in-season moisture availability (Asseng et al. 2004; Lanning et al. 2010; He et al. 2012). Kouadio et al. (2015) identified earlier seeding in western Canada as one method to reduce the risks associated with increased temperatures during the growing season as a result of climate change. In the evaluations of Kouadio et al. (2015) the lowest yield loss was observed from the earliest seeding dates. Many studies have indicated higher grain yield from seeding wheat earlier in western Canada (Larter et al. 1971; Mckenzie et al. 2008; McKenzie et al. 2011; Lanning et al. 2012) however, few have indicated the point at which seeding earlier has a detrimental effect on

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[1] *This chapter has been published in:* G. R. S. Collier, D. M. Spaner, R. J. Graf, and B. L. Beres. 2020. The integration of spring and winter wheat genetics with agronomy for ultra-early planting into cold soils. *Frontiers in Plant Science* 11:89. doi 10.3389/fpls.2020.00089

yield. Thilakarathna et al. (2017) evaluated frost-seeding, or seeding prior to spring ground thaw, in Ontario, Canada and determined a grain yield benefit of up to 24% over conventional seeding times for spring wheat in that environment, despite increased plant mortality.

The objective of this study was to evaluate an ultra-early spring wheat seeding system beginning at soil temperatures of 0°C. Ultra-early seeding treatments were combined with and without specialized cold-tolerant spring wheat genetics to determine if reductions in grain yield, grain quality, or growing system stability are associated with ultra-early seeding into cold soils in the Northern Great Plains.

2.2 Materials and methods

2.2.1 Site description, experimental design, and seeding date determination

This study was conducted at six sites in western Canada over 4 years, 2015–2018, totaling 13 site years (Table 2-1). The treatment structure consisted of a factorial arrangement of 24 treatments based on four wheat lines, six planting dates, and four replicates blocked within replicate by planting date. The lines used were "AC Stettler" (DePauw et al. 2009), an industry standard Canada Western Red Spring (CWRS) wheat, and three cold tolerant experimental lines (LQ1282A, LQ1299A, LQ1315A) developed by intercrossing two previously identified cold tolerant lines derived from a cross between "Norstar" (Grant 1980) Canada Western Red Winter (CWRW) wheat and "Bergen," a Dark Northern Spring (DNS) wheat grown in North Dakota and developed in the United States of America (Table 2-2). The seeding dates were based on soil temperature triggers of 0, 2, 4, 6, 8, and 10°C as measured with an Omega™ TPD42 soil temperature probe at 5 cm depth at 10:00 AM each day prior to seeding. If soil conditions made seeding impossible at the first soil temperature trigger (0°C), each seeding date was adjusted so that there was a 2°C soil temperature differential between each successive seeding date. The initial seeding date at each site in each year is shown in Table 2-1. In general, soil conditions at the sites south of 51°N allowed seeding to occur at targeted soil temperatures, while seeding at the sites north of 51°N began as soon as planting equipment could access trial sites and continued with 2°C soil temperature intervals between seeding dates. Access to trial sites at the higher latitude locations was often limited at 0°C soil temperatures due to excessive moisture and saturated soil after snow ablation.

2.2.2 Cold tolerant wheat lines

The cold-tolerant wheat lines used in this study were the result of work completed at Agriculture and Agri-Food Canada Lethbridge and the University of Guelph, where a proof of concept study successfully demonstrated the transfer of high levels of cold tolerance from Norstar winter wheat to spring wheat (Larsen, 2012). Briefly, spring growth habit, doubled haploid lines from a Bergen × Norstar cross were screened using an LT_{50} test to discover lines with exceptional cold tolerance. LT_{50} tests or lethal temperature tests, evaluate cold tolerance by identifying the temperature at which 50% mortality occurs among seedling plants (Fowler 2008). Two of the best cold tolerant spring growth habit lines were intercrossed (A134$S10 × A134$S17) to develop lines with improved agronomics. Transfer of cold tolerance to spring wheat was successful, as several lines exhibited LT_{50} values superior to some commercial winter wheats commonly grown in eastern Canada. Thirty-nine semi-dwarf $F_{5:7}$ derived cold tolerant lines were placed into a non-replicated preliminary yield trial established in Lethbridge in the fall of 2013 to identify superior lines. The same lines were increased and spring growth habit was confirmed at the Agriculture and Agri-Food Canada winter nursery in New Zealand over the winter of 2013/14. In the spring of 2014, both a yield trial and seed increase were established at Lethbridge to provide a robust data set of crop response variables (data not shown) which was used to select the three lines for this study (LQ1282A, LQ1299A, LQ1315A). In addition to cold tolerance, the selection criteria included high grain yield, grain protein content, and straw strength, and reduced plant height and days to maturity.

2.2.3 Seeding operations, nutrient management and pest management

Seeding equipment varied but was similar to the drill designed and built by Agriculture and Agri-Food Canada Lethbridge, which was configured with ConservaPak™ knife openers (8) spaced 24 cm apart, a Valmar™ air delivery system, a Raven™ hydraulic seed calibration and product control system, and Morris™ seed cups. Fertilizer was banded to the side and below the seed row at seeding and was applied based on soil test recommendations and regional yield expectations. All seed was treated with a fungicide seed treatment to control seedling diseases [Raxil PRO—tebuconazole ({RS}-1-p-chlorophenyl-4,4-dimethyl-3-{1H-1,2,4-triazol-1-ylmethyl}pentan-3-ol] 3.0 g L^{-1} + prothioconazole [(RS)-2-[2-(1-chlorocyclopropyl)-3-(2-chlorophenyl)-2-hydroxypropyl]-2,4-dihydro-1,2,4-triazole-3-thione] 15.4 g L^{-1} + metalaxyl [metyl N-(methoxyacetyl)-N-2,6-xylyl-DL-alanite] 6.2 g L^{-1} Bayer Crop Science Canada Inc., Calgary, AB). All wheat lines were seeded at 400 viable seeds m^{-2}.

Weed control was achieved with in-crop herbicide applications at the Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie (BBCH) scale 12–22 stage of wheat, generally in late May. Due to variable staging between seeding dates, herbicide products with restrictive crop staging or residual properties were not used. All post-emergent herbicide applications were made using a motorized sprayer calibrated to deliver a carrier volume of 45 L ha^{-1} at 275 kPa pressure.

2.2.4 Data collection

Plant counts for each plot were performed from BBCH 20 to BBCH 49 to indicate total viable plants in two one metre long areas in the second and third rows and the second and third last rows of the plot. These areas were staked and used to count the number of heads later in the growing season. Heads $plant^{-1}$ was calculated using the number of heads divided by the initial plant count for each staked area. Days to emergence were determined when 50% of plants in a plot had emerged. Crop anthesis was recorded in days from planting to when 50% of the heads in a plot began extruding anthers. Plant height was recorded from two randomly picked but representative areas of the plots and the height of five spikes, excluding awns, was measured.

The entire plot was harvested with a plot combine. The combine was equipped with a straight-cut header, pickup reel, and crop lifters. Grain yield per plot was weighed after drying the sample to 14% moisture content, and used to estimate total yield per ha (Mg ha^{-1}). A 2 kg subsample of grain was used to determine seed mass (from 250 kernels) and grain bulk density (kg hl^{-1}). Whole grain protein concentration was determined from the same subsample using near infrared reflectance spectroscopy technology (Foss Decater GrainSpec, Foss Food Technology Inc, Eden Prairie, MN) (Irvine et al. 2013).

2.2.5 Statistical analyses

Data were analyzed in the MIXED procedure of SAS, and any outlier observations were removed before a combined analysis over years and environments (site-year) was performed using site-year, replication, soil temperature at seeding, and wheat variety as variables in the CLASS statement (Littell et al. 2006; SAS Institute 2009). Error variances were heterogeneous among the environments, and corrected Akaike's information criterion (AICc) on model fit indicated that modeling residual variance heterogeneity improved fit. Variance heterogeneity was modeled for all analyses using the random statement in PROC MIXED with the group option set to environment. Environment and the interactions associated with environment were considered as random effects, whereas the treatment effects were considered fixed and significant if $P \leq 0.05$ when the analysis was performed (Steel et al. 1997). Analyses were performed for environment groupings based on latitude. Sites north and south of 51° latitude were placed into two groups and analyzed separately (Figure 2-1).

The effect of planting date on yield was further evaluated with an analysis of covariance (ANCOVA) following the method developed by Yang and Juskiw (2011). The implementation of ANCOVA reduced the error mean square, accounted for missing data, and served to increase the precision of the resulting regression analysis. Planting date was considered a covariate and classification variable by generating a second column of data (s) identical to the planting date to be used as the covariate. Type 1 sums of squares was specified via the METHOD statement in PROC MIXED (Yang and Juskiw, 2011). Direct regression variables (covariates) s and s*s represent linear and quadratic responses to planting date and are part of the MODEL statement. Environment or group interactions with s and s*s are used to evaluate linear and quadratic responses that are heterogeneous relative to planting date. Initial ANCOVA analysis indicated a significant interaction between s*environment which supports the decision to analyze the environments in two groups based on latitude.

A biplot grouping methodology was used to explore system responses and variability of wheat yield as described by Francis and Kannenberg (1978). The mean and coefficient of variation (CV) across years and replications were estimated for each treatment combination. Means were plotted against CV, and used to categorize the biplot data into four quadrants/groups, which included high mean grain yield and low variability (group I), high mean grain yield and high variability (group II), low mean grain yield and high variability (group III), and low mean grain yield and low variability (group IV).

2.3 Results and discussion

2.3.1 Growing season variability and environmental conditions

Initial seeding date varied within locations across years. Seeding began early in 2016 - February 16 in Lethbridge, March 29 in Edmonton. The 2017 and 2018 seasons experienced delayed seeding due to late spring thaw. The first seeding date in Lethbridge in 2016 was 66 days earlier than the first seeding date in 2018. The first seeding date in Edmonton in 2016 was 37 days earlier than the first seeding date in 2017. Initial seeding dates by year and location are listed in Table 2-1. The wide range of environmental conditions that were experienced through the course of this study would be considered typical for the Northern Great Plains region as reported by Shen et al. (2005) who found no long term trends for the start of the growing season, defined as the first day of the year when five consecutive days have a mean temperature of 5°C, end of the growing season, the first day in the fall the mean temperature is below 5°C, and length of the growing season in the region. Shen et al. (2005) reported no change in the growing season despite reporting significant increases in frost free growing period, later first fall frosts, and earlier final spring frosts. The lack of an identifiable trend in growing season length, beginning, and end support the adoption of a soil-temperature-based seeding trigger system to standardize planting date from year to year and take advantage of the increased frost-free period as opposed to the traditional use of calendar date as a reference point.

Precipitation varied over the duration of the study. Precipitation in 2015 was below average at all trial locations. In 2016 precipitation was above 30-year averages at all locations except Lethbridge, which was 89% of the 30-year average. All sites in 2017 and 2018 received below average rainfall (Table 2-1).

Eight of 13 site years experienced ambient air temperatures of −5°C or lower after initial seeding; some sites experienced temperatures as low as −9.8°C and −10.2°C. One site did not experience a nighttime low below 0°C after the initial seeding date. On average, sites had 16.5 nights where air temperatures reached below freezing, the most severe being Lethbridge in 2016 and 2017 where the air temperature dropped below 0°C for 37 and 36 nights respectively (Table 2-1).

After the initial planting date, nights with air temperatures below freezing averaged 21 at the sites south of 51°N and 12.5 at the sites north of 51°N. The soils at the sites south of 51°N tended to be free of snow cover and excess moisture and reached 0°C earlier than the sites north of 51°N. However, once sites north of 51°N reached 0°C they warmed faster than the sites south of 51°N, meaning planting dates were closer together at the sites north of 51°N (Table 2-3). This is due to the later disappearance of snow cover, increased available solar radiation when sites north of 51°N reached 0°C, and greater heat holding capacity of heavier texture clay loam soils relative to the sites south of 51°N (Zhao et al. 2002). The trial sites north of 51°N include soils classified as gray wooded Luvisols, orthic black chernozems, and orthic dark brown chernozems. The trial sites south of 51°N include soils of orthic dark brown chernozem and orthic brown chernozem classes. The aforementioned differences in environmental and soil conditions required the environments in this study to be divided into two groups; on this basis 51°N latitude was used as a divisional line between northern and southern environments.

Wheat emergence was slowed by the cool, slowly warming soils of sites south of 51°N. Wheat seeded at the earliest planting dates in the sites south of 51°N required 9.5 days longer to emerge than the earliest planting dates at the sites north of 51°N (Table 2-3).

2.3.2 Seeding date effect

Planting date did not alter yield at sites north of 51°N ($P = 0.158$) (Table 2-4). There was a yield response to planting date at sites south of 51°N ($P = 0.025$), and significant linear and quadratic effects of planting date on grain yield ($P = 0.044$ and $P = 0.03$ respectively) (Tables 2-4 and 2-5). The greatest grain yield occurred at the second and third planting dates, which correspond to soil temperature increase of 2 and 4°C after the earliest feasible planting date. Grain yield was lower at the earliest and latest seeding date (Table 2-5, Figure 2-2). The earliest seeding date produced less grain than the second and third seeding dates, however it did not produce less grain than the fourth or fifth seeding dates and yielded more grain than the latest seeding date. The optimum seeding time at sites south of 51°N in the Northern Great Plains of Canada is between soil temperatures of 2 and 6°C after the first possible seeding date (Figure 2-2). The regression equation determined in this study indicates a maximum grain yield is realized when seeding occurs prior to when soil temperatures reach 3.9°C. Planting as early as possible after soil temperature has reached 0°C, will result in the same grain yield as delaying seeding until soil temperatures warm by 7.7°C (Figure 2-2). Seeding after a soil temperature of 7.7°C above the first feasible seeding date will yield less grain than seeding as early as possible after ground thaw. Seeding dates prior to spring thaw as evaluated by Thilakaranthna et al. (2017) are often met with equipment and logistical restraints in western Canada. Seeding attempts prior to soil reaching 0°C in western Canada may be better served by fall seeding of winter wheat which has additional agronomic benefits as reviewed by Larsen et al. (2018).

Grain yield at sites south of 51°N is limited by lower precipitation and greater heat stress relative to sites located north of 51°N (Table 2-1, Figure 2-2). Delayed seeding at sites south of 51°N resulted in lower grain yield due to reduced water availability and daylight hours and increased temperature during critical grain fill periods (Farooq et al. 2011). Anthesis to maturity and emergence to maturity periods were not significantly different at any seeding dates at sites south of 51°N (Table 2-3). However, anthesis to maturity and emergence to maturity periods were offset as a result of seeding date. The length of days and available solar radiation captured in the anthesis to maturity and emergence to maturity periods of the earlier planting dates was greater than at the later planting dates.

Sites north of 51°N had no grain yield difference as a result of seeding date. Rapid soil temperature increases decreased time differential between each seeding date. Greater moisture availability and longer periods from anthesis to maturity compensated for potential grain yield loss associated with delayed seeding (Table 2-3).

Wheat is highly amenable to ultra-early seeding into cold soils; no negative yield effect relative to later plantings north or south of 51°N was discernable. Planting as early as possible had less negative effect on spring wheat yield than delaying seeding until soils had warmed 8 to 10°C (Figure 2-2).

Grain protein concentration, grain thousand kernel weight, and grain test weight were not affected by seeding date. Ultra-early seeding did not result in changes in grain quality despite increased grain yield in some environments. Previous studies have indicated increased grain yield is associated with decreased grain protein concentration (Iqbal et al., 2007a). Further evaluation is required to determine if ultra-early seeding can consistently result in greater grain yield without decreasing grain protein concentration.

Plant height was shorter at seeding dates two, three, and four at sites north of 51°N, while earlier and later seeding treatments were taller. The effect of seeding date on plant height had a significant positive quadratic association at sites north of 51°N (Table 2-6). Plant height at sites south of 51°N was not affected by seeding date.

The number of heads m^{-2} significantly decreased with delayed seeding at sites south of 51°N (Table 2-4). A significant negative linear effect for reduced number of heads m^{-2} and no significant difference in the number of heads $plant^{-1}$, indicate that despite the extreme environmental conditions experienced when seeded ultra-early, the early planted wheat had better survivability than later seeded wheat, which did not initiate additional tillering to compensate for decreased plant stand (Table 2-5).

2.3.3 Effect of cold tolerant wheat lines

Treatment effects were present for all reported variables in sites north and south of 51°N except for heads $plant^{-1}$ in sites south of 51°N. Significant effects are the result of class differences between AC Stettler and the cold tolerant wheat lines LQ1282A, LQ1299A, and LQ1315A (Table 2-2). AC Stettler is a milling quality wheat of the CWRS class. The CWRS class wheats have high grain protein concentration, typically over 13.5%, which reduces grain yield potential (Iqbal et al. 2007a; Prairie Grain Development Committee 2015). The cold tolerant lines used in this study are not registered varieties and have not been evaluated by the Prairie Grain Development Committee or the Canadian Grain Commission; however, the end-use characteristics of these lines indicate a likely classification of Canada Western Special Purpose (CWSP). CWSP wheats have reduced grain protein content and greater yield potential than CWRS wheats.

AC Stettler had higher grain protein content at all sites. At sites north of 51°N AC Stettler yielded less grain than the cold tolerant lines. At sites south of 51°N AC Stettler yielded less grain than LQ1282A, but yielded the same as LQ1299A, and LQ1315A (Tables 2-5 and 2-6). Grain yield of longer maturing cold tolerant wheat lines at sites south of 51°N may have been limited by reduced water availability and higher temperatures during grain fill. At sites south of 51°N AC Stettler had greater thousand kernel weight, grain test weight and heads m^{-2} values than the cold tolerant lines, additionally, there were no differences in heads $plant^{-1}$ between AC

Stettler and cold tolerant lines. Greater heads m^{-2} and no difference in heads $plant^{-1}$ indicate the survival of AC Stettler was at least as good as the survival of the cold tolerant lines under ultra-early planting conditions.

2.3.4 Ultra-early seeding system stability

A version of the Francis and Kannenberg (1978) biplot grouping method was used to help visualize the stability of ultra-early wheat seeding systems. The biplots for yield suggest advantages to an ultra-early seeding system in sites south of 51°N. Seeding dates two and three had the greatest yield and lowest variability (Figure 2-3A). Seeding date four maintained high grain yield, but variability increased at this seeding date. Seeding dates one, five, and six tended to result in higher variability and lower grain yield than seeding dates two, three, or four. AC Stettler consistently yielded less grain than the cold tolerant lines, but the stability of yield across seeding dates was similar to the cold tolerant varieties, as indicated by similar CV values.

Seeding date did not affect grain yield at sites north of 51°N. The biplot in Figure 2-3B shows mixed system stability responses to seeding date and grain yield. All seeding dates except seeding date three are represented by at least one data point in group I (high yield and low variability). Seeding ultra-early at sites north of 51°N did not reduce grain yield or system stability relative to delayed seeding.

An ultra-early wheat seeding system on the Northern Great Plains is feasible with few changes from current management systems. Grain yield was not negatively impacted by seeding very early and in some areas resulted in increased grain yield. At sites south of 51°N where seeding date had a significant effect on yield, the earliest seeding date did not result in different grain yield from the fourth or fifth seeding date, and resulted in a higher grain yield than the final seeding date. We conclude that seeding spring wheat in the Northern Great Plains region of Canada can begin as soon as soil temperatures are above 0°C and seeding equipment can access fields. Ultra-early seeding did not result in decreased growing system stability or lower grain yield than delaying seeding until soil temperatures warmed 8 to 10°C. In sites south of 51°N growing system stability increased with ultra-early seeding.

The use of cold tolerant lines did not increase growing system stability relative to the conventional check variety AC Stettler. Based on studies by Fowler (2008), it was postulated that the ability of the cold tolerant spring wheat lines to acclimate to a relatively low LT_{50} would provide a useful genetic resource for enhanced cold temperature protection of commercial spring wheat varieties when seeded at ultra-early seeding dates, provided that there was adequate time for cold acclimation. These results, relative to AC Stettler, showed that for ultra-early spring wheat seeding, additional genetic cold temperature protection and increased rates of cold acclimation did not confer an advantage to the crop.

Currently in western Canada crop insurance systems maintain limits for the latest seeding dates a grower can plant a crop and receive compensation. The results of this study indicate that an incentive program to encourage early seeding may limit risk, increase grain yield potential, and increase growing system stability relative to current practices.

2.4 Conclusions

Recommendations generated from this study are for growers to begin shifting to earlier spring wheat planting in western Canada—planting may begin immediately after the soil reaches 0°C, or as early as fields allow seeding operations to commence. A shift to seeding based on soil temperature triggers can normalize planting times within the growing season more effectively than seeding based on calendar date or on last expected spring frost. Special cold tolerant lines evaluated in this study did not benefit grain yield or stability of an ultra-early growing system. This study indicates that ultra-early seeding has no detrimental effect on yield on the Northern Great Plains and can potentially increase grain yield in lower latitude regions of western Canada. As indicated by Asseng et al. (2004); Lanning et al. (2010); He et al. (2012), and Kouadio et al. (2015), the risk of reduced grain yield in western Canada caused by increases in average growing season temperature and reduced precipitation can potentially be avoided by continually shifting wheat planting windows earlier. Future work will develop best management practices for an ultra-early wheat seeding system in western Canada and evaluate the benefits of optimized agronomic systems.

2.5 Acknowledgements

Thank you to the support of staff at Agriculture and Agri-food Canada Lethbridge (Ryan Dyck, Steve Simmill, Warren Taylor, and a small regiment of seasonal workers and summer students); Agriculture and Agri- Food Canada Scott (Cindy Gampe and Arlen Kapiniak); the staff at the

University of Alberta (Klaus Strenzke, Dr. Muhammad Iqbal, Fabiana Dias, Joseph Moss, Tom Keady, Katherine Chabot, and Russell Puk); the British Columbia Grain Producers Association; and many others at each mentioned location. Special thanks to Craig Stevenson and Erin Collier for support with statistical analyses and manuscript editing. This study was funded through the Agricultural Funding Consortium with funds provided by Alberta Innovates BioSolutions, the Alberta Wheat Commission, and the Western Grain Research Foundation Grant number 2014F172R.

2.6 Tables

Table 2-1. Average precipitation, post-seeding air temperature extremes and cumulative freezing events for each location × year.

Location	Latitude/Longitude	Agroecological Region	Soil Zone	Average Yearly Precipitation* (mm)	Year	Actual Precipitation (mm)	Earliest Seeding Date**	Number of days with air temperature below 0ºC after initial seeding date	Lowest air temperature recorded after seeding (ºC)
Dawson Creek, BC	55º48’N 120º14’W	Parkland	Grey Wooded	453	2015	325	April 16	12	-5.0
					2016	542	April 21	11	-6.1
Edmonton, AB	53º33’N 113º29’W	Parkland	Black	446	2015	299	April 9	12	-4.2
					2016	510	March 29	11	-3.6
					2017	416	May 5	0	2.3
Lethbridge, AB	49º41’N 112º50’W	Western Prairies	Dark Brown	380	2015	251	March 6	37	-6.7
					2016	338	February 16	36	-10.2
					2017	249	March 20	17	-7.6
					2018	284	April 23	2	-1.2
Regina, SK	50º26’N 104º35’W	Western Prairies	Dark Brown	397	2015	347	April 21	11	-5.0
Scott, SK	52º21’N 108º49’W	Western Prairies	Dark Brown	366	2016	415	April 2	21	-9.8
					2017	300	March 31	27	-9.4
Swift Current, SK	50º18’N 107º46’W	Western Prairies	Brown	357	2015	304	April 10	23	-6.4

* 1981-2010 average yearly precipitation accumulation. ** Based on 0ºC soil temperature trigger date

Table 2-2. Classification of check, cold tolerant lines, and parent wheat lines.

Cultivar	Parental Lines	Parental Lines Canadian Wheat Classification	Experimental Designation	Reference
AC Stettler*	Prodigy*/Superb*	CWRS/CWRS	Commercial Check	DePauw et al. 2009
LQ1282A****	Norstar**/Bergen***	CWRW/DNS	Cold Tolerant[Ŧ]	Larsen 2012
LQ1299A****	Norstar/Bergen	CWRW/DNS	Cold Tolerant[Ŧ]	Larsen 2012
LQ1315A****	Norstar/Bergen	CWRW/DNS	Cold Tolerant[Ŧ]	Larsen 2012

Ŧ Cold tolerant lines were selected from 92 double haploid lines from a Norstar/Bergen cross initially completed at AAFC Lethbridge. Cold tolerant lines were selected based on demonstrated cold tolerance using LT_{50} tests as described in Larsen (2012). Further selection criteria included yield and quality parameters.

* Canada Western Red Spring (CWRS)

** Canada Western Red Winter (CWRW)

*** Dark Northern Spring (DNS) United States of America hard red spring wheat class.

**** Undetermined

Table 2-3. Least square means values and significance of crop development stage duration in ultra-early seeded wheat.

Planting Date[Ŧ]	Days to Emergence	Days to Anthesis	Days to Maturity	Emergence to Anthesis (Days)	Anthesis to Maturity (Days)	Emergence to Maturity (Days)
Sites South of 51° N latitude						
1 (Earliest)	23	79	140	56	60	117
2	22	82	138	60	56	116
3	21	76	136	56	60	115
4	18	76	135	58	59	117
5	13	69	131	55	62	117
6 (Latest)	13	65	125	53	60	113
F-Test	***	***	**	**	NS	NS
SED	1.6	2.6	3.9	1.8	NS	NS
Linear	***	***	***	*	NS	NS
Quadratic	NS	*	NS	*	NS	NS
Sites North of 51° N latitude						
1	19	78	123	59	45	104
2	19	77	122	57	45	102
3	17	73	119	56	46	102
4	15	69	116	54	47	101
5	12	66	113	53	48	101
6	9	62	111	53	49	102
F-Test	***	***	***	***	*	*
SED	1.5	1.4	2.0	0.7	1.1	1.0
Linear	***	***	***	***	***	**
Quadratic	NS	NS	NS	*	NS	NS

Data not reported for all environments. Sites south of 51° latitude include Lethbridge, AB. 2017, 2018. Sites north of 51° latitude include Dawson Creek, BC. 2016, Edmonton, AB. 2016, 2017, Scott, SK. 2016, 2017. (***) Significant at $P < 0.001$. (**) Significant at $P < 0.01$. (*) Significant at $P < 0.05$. (NS) Not Significant. (SED) Standard error of the difference. (Ŧ) Planting date as determined by soil temperature trigger temperatures. Planting Date (PD) 1 corresponds to a soil temperature of 0°C, or as soon after this trigger soil temperature as the site could be planted. Each successive PD corresponds to a 2°C increase in soil temperature from the previous PD.

Table 2-4. Probability values from the analysis of variance for each dataset for the fixed effects of planting date and wheat line. Environments, replicates within each environment, and interactions between random and fixed effects are considered to be random.

	Yield (Mg ha^{-1})	Protein (%)	Test Weight (kg hL^{-1})	Thousand Kernel Weight (g)	Height (cm)	Heads m^{-2}	Heads $plant^{-1}$
Sites South of 51° N latitude[Ŧ]							
Planting Date (PD)	**0.025**	0.072	0.67	0.75	0.051	**<0.001**	0.73
Wheat Line (WL)	**0.044**	**<0.001**	**<0.001**	**<0.001**	**0.047**	**0.023**	0.86
PD_{Linear}	**0.030**	**0.009**	0.54	0.26	**0.014**	**<0.001**	0.28
$PD_{Quadratic}$	**0.0047**	0.18	0.14	0.33	0.47	0.36	0.78
PD × WL	0.48	1.0	0.98	0.98	0.17	0.97	0.57
Sites North of 51° N latitude[‡]							
Planting Date (PD)	0.16	0.21	0.60	0.091	**0.008**	0.28	0.14
Wheat Line (WL)	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.006**	**<0.001**	**<0.001**
PD_{Linear}	0.84	**0.015**	0.22	**0.005**	0.15	**0.039**	**0.028**
$PD_{Quadratic}$	0.22	0.33	0.52	0.86	**0.001**	0.31	0.54
PD × WL	0.95	0.91	0.94	1.0	0.81	0.96	0.88

[Ŧ] 6 site years. Lethbridge, AB 2015, 2016, 2017, 2018. Regina, SK 2015, Swift Current, SK 2015

[‡] 7 site years. Dawson Creek, BC 2015, 2016. Edmonton, AB 2015, 2016, 2017. Scott, SK 2016, 2017. Bolded values indicate a p-value of less than 0.05.

Table 2-5. Least square means values and significance of treatment interactions for sites south of 51°N latitude.

Planting Date Ŧ	Yield (Mg ha^{-1})	Protein (%)	Test Weight (kg hL^{-1})	Thousand Kernel Weight (g)	Height (cm)	Heads m^{-2}	Heads plant^{-1}
1 (Earliest)	2.89	12.0	77.3	30.4	70	345	1.3
2	3.04	11.9	77.6	30.5	71	362	1.3
3	3.04	12.2	77.6	30.6	71	337	1.4
4	2.94	12.1	77.7	30.3	70	286	1.3
5	2.93	12.3	77.4	30.4	68	298	1.1
6 (Latest)	2.68	12.6	77.1	29.7	69	270	1.2
F-Test	*	NS	NS	NS	NS	***	NS
SED	0.12					56	
Linear	*	**	NS	NS	*	***	NS
Quadratic	**	NS	NS	NS	NS	NS	NS
Wheat Line							
LQ1282A	3.00	11.5	77.3	28.2	70	318	1.3
LQ1299A	2.90	11.8	76.4	30.9	69	307	1.3
LQ1315A	2.91	11.8	77.2	30.4	70	309	1.3
AC Stettler	2.86	13.6	78.8	31.7	71	332	1.3
F-Test	*	***	***	***	*	*	NS
SED	0.06	0.14	0.2	0.3	1	11	
Planting Date × Wheat Line	NS	NS	NS	NS	NS	NS	NS

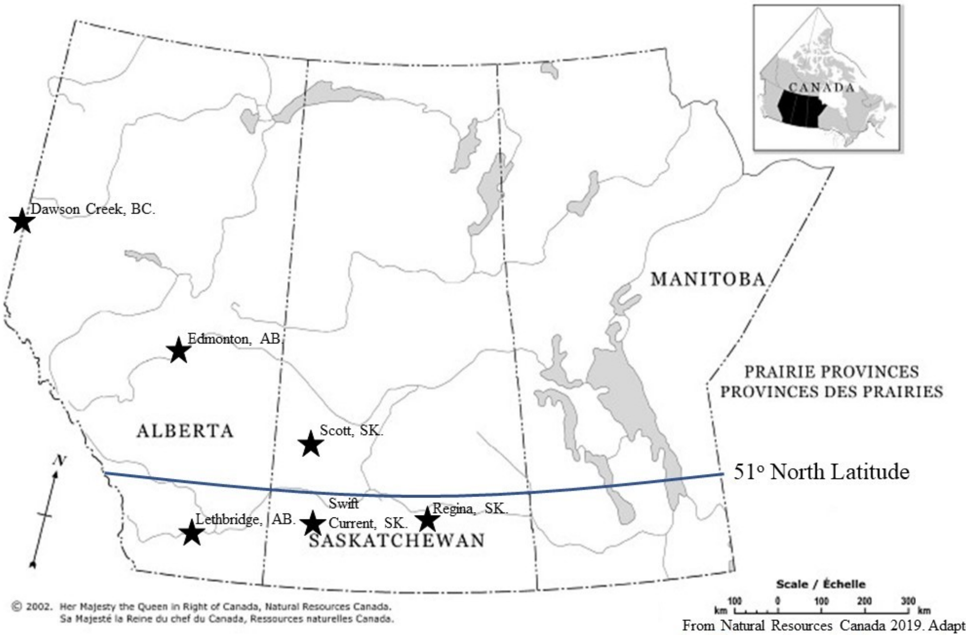
(***) Significant at $P < 0.001$. (**) Significant at $P < 0.01$. (*) Significant at $P < 0.05$. (NS) Not Significant. (SED) Standard error of the difference. (Ŧ) Planting date as determined by soil temperature trigger temperatures. Planting Date (PD) 1 corresponds to a soil temperature of 0°C, or as soon after this trigger soil temperature as the site could be planted. Each successive PD corresponds to a 2°C increase in soil temperature from the previous PD.

Table 2-6. Least square means values and significance of treatment interactions for sites north of 51° N latitude.

Planting Date Ŧ	Yield (Mg ha^{-1})	Protein (%)	Test Weight (kg hL^{-1})	Thousand Kernel Weight (g)	Height (cm)	Heads m^{-2}	Heads $plant^{-1}$
1 (Earliest)	5.69	12.4	79.0	35.0	82	464	2.0
2	5.35	12.6	78.8	35.4	81	460	2.0
3	5.17	12.6	78.9	35.5	79	457	1.8
4	5.54	12.9	78.8	35.6	80	454	1.8
5	5.62	12.9	78.9	36.6	82	451	1.9
6 (Latest)	5.44	12.8	78.4	36.7	83	426	1.8
F-Test	NS	NS	NS	NS	**	NS	NS
SED					1		
Linear	NS	*	NS	**	NS	*	*
Quadratic	NS	NS	NS	NS	**	NS	NS
Wheat Line							
LQ1282A	5.74	11.4	78.5	33.2	82	455	1.9
LQ1299A	5.48	12.2	78.1	36.4	80	417	1.7
LQ1315A	5.51	12.1	78.8	36.2	81	447	1.8
AC Stettler	5.14	15.2	79.8	37.4	81	491	2.0
F-Test	***	***	***	***	**	***	***
SED	0.10	0.2	0.2	0.3	1	7	0.1
Planting Date × Wheat Line	NS	NS	NS	NS	NS	NS	NS

(***) Significant at *P* < 0.001. (**) Significant at *P* < 0.01. (*) Significant at *P* < 0.05. (NS) Not Significant. (SED) Standard error of the difference. (Ŧ) Planting date as determined by soil temperature trigger temperatures. Planting Date (PD) 1 corresponds to a soil temperature of 0ºC, or as soon after this trigger soil temperature as the site could be planted. Each successive PD corresponds to a 2ºC increase in soil temperature from the previous PD.

2.7 Figures



From Natural Resources Canada 2019. Adapted by G. Collier
http://ftp.geogratis.gc.ca/pub/nrcan_rncan/raster/atlas_6_ed/reference/bilingual/prairies_out.jpg

Figure 2-1. Geographical distribution of test locations for the assessment of ultra-early wheat planting in western Canada 2015 to 2018. (The Atlas of Canada – Natural Resources Canada). Modified by G. Collier. http://ftp.geogratis.gc.ca/pub/nrcan_rncan/raster/atlas_6_ed/reference/bilingual/prairies_out.jpg).

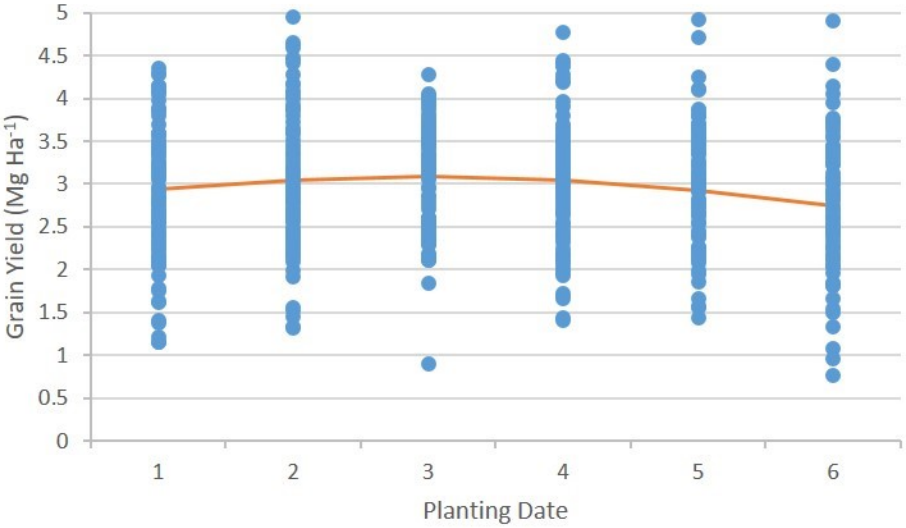


Figure 2-2. Wheat grain yield as a function of planting date (PD) in sites south of 51°N latitude. PD 1 corresponds to a soil temperature of 0°C, or as soon after this trigger soil temperature as the site could be planted. Each successive PD corresponds to a 2°C increase in soil temperature from the previous PD.) The line represents a quadratic regression for grain yield [yield = 2.7709 + (0.2125 × PD) − (0.03624 × PD^2): $R^2 = 0.61$***] (***) Significant at $P < 0.001$.

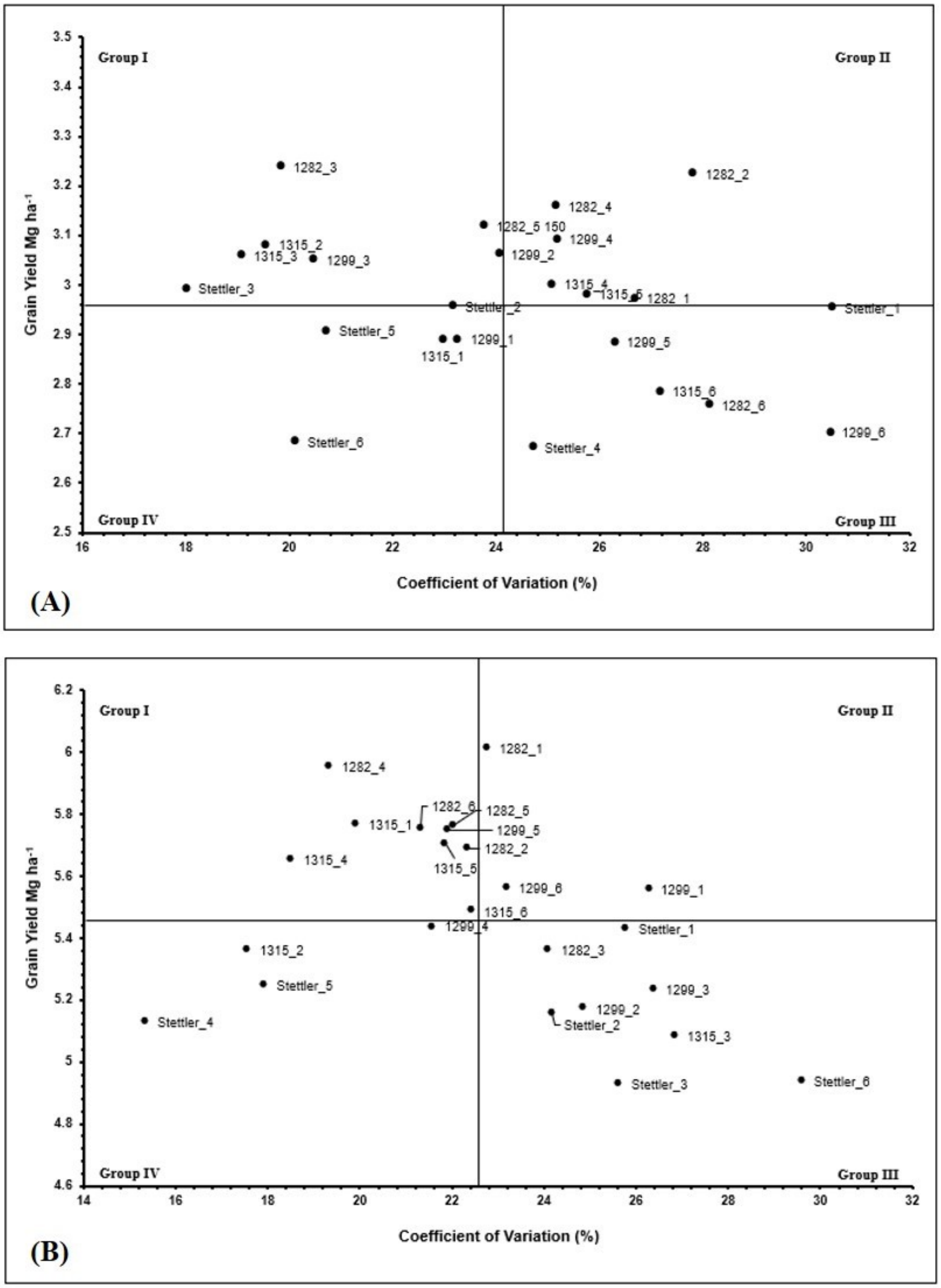


Figure 2-3. Biplots summarizing yield means vs. coefficient of variation (CV) for (A): sites south of 51°N latitude, (B) sites north of 51°N latitude. Abbreviations are as follows: I) first number/name represents the wheat line (AC Stettler, LQ1282A, LQ1299A, and LQ1315A). II) Second number represents planting date (1–6). Grouping categories: group I: high mean, low variability; group II: high mean, high variability; group III: low mean, high variability; group IV: low mean, low variability.

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3.0 Optimal agronomics increase grain yield and grain yield stability of ultra-early wheat seeding systems[2]

3.1 Introduction

Canada is a key global producer of high-quality spring wheat (*Triticum aestivum L.*), and in 2018 was the world's third largest exporter (19.7 MT) and sixth largest producer (31.8 MT) of wheat (FAOSTAT 2020). Spring wheat production in western Canada has increased from an annual average of 14.3 MT (1961 – 1970) to 19.8 MT (2008 – 2017), while the annual area seeded to spring wheat decreased by 31% over the same period (Statistics Canada 2020). The average annual grain yield increase over this period, from 1.5 MT to 3.0 MT per million hectares, is attributed to improved wheat genetics and agronomic management, increased and more efficient fertilizer use, and adoption of technology and mechanization (Beres et al. 2020). A short frost-free period is commonly referenced as a grain yield limiting factor on the northern Great Plains; however, increases in the average frost-free period from 1961 to 2018 are rarely referenced as contributing to wheat grain yield increase (He et al. 2018; Iqbal et al. 2016; Drury et al. 2014; Thomas and Graf 2014). Ultra-early wheat seeding systems based on soil temperature triggers as described in Collier et al. (2020) can produce greater grain yield by capturing the benefits of longer frost-free periods: early season growing degree-day accumulation, increased vegetative growth periods, early season precipitation, increased day-length at anthesis and reduced average temperatures at grain fill.

Iqbal et al. (2007) reported one of the primary limiting factors of wheat grain yield on the northern Great Plains was the short frost-free period that limits the length of the growing season. Lanning et al. (2010) investigated the yield of 'Thatcher' wheat from six locations in Montana, USA, over 56 seasons and reported a grain yield increase of 23.5 kg ha^{-1} yr^{-1} and an average planting window shift of 0.24 days yr^{-1} earlier. The grain yield increase of 'Thatcher' was attributed to earlier planting and longer growing seasons. Cutforth et al. (2004) calculated the average frost-free period in western Canada to be 114 days in 2000, an increase of 28 days from

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[2] *This chapter has been published in:* G. R. S. Collier, D. M. Spaner, R. J. Graf, and B. L. Beres. 2021. Optimal agronomics increase grain yield and grain yield stability of ultra-early wheat seeding systems. *Agronomy* 11, 240. doi 10.3390/agronomy11020240

the average frost-free period of 96 days in 1940. This increase was a result of both earlier final spring frosts and later first fall frosts. The shift to earlier final spring frosts has been accompanied by a corresponding increase in average growing season temperature. This can decrease wheat grain yield due to increased daily temperature maximums and fewer precipitation events during grain fill (Asseng et al. 2019; He et al. 2012; Lanning et al. 2010; Asseng et al. 2004). Studies investigating wheat and small grain cereals seeding dates have found the greatest yield resulted from the earliest seeding dates (Larter et al. 1971; Briggs and Aytenfisu 1979; McKenzie et al. 2008; McKenzie et al. 2011; and Lanning et al. 2012). However, these studies based initial seeding on calendar date, meaning the planting times within individual seasons were not standardized to account for variability between growing seasons – an issue accounted for by moving to soil temperature-triggered seeding in the study conducted by Collier et al. (2020). Multiple studies have identified earlier seeding as an important method to avoid grain yield reduction caused by increased growing season temperatures (Collier et al. 2020; Qian et al. 2019; Kouadio et al. 2015; and He et al. 2012). Specifically, Kouadio et al. (2015) found the least yield loss due to increased temperatures during grain fill occurred in earlier seeded wheat.

Collier et al. (2020) investigated ultra-early wheat seeding on the northern Great Plains using conventional and cold-tolerant spring wheat lines and seeding times based on soil temperature triggers of 0°C through 10°C. This study reported that ultra-early seeding maintained grain yield, and that ultra-early seeding was not dependent on the concurrent development of cold tolerant spring wheat genetics. The latest planting time in the study, based on a 10°C soil temperature trigger, resulted in the lowest yield at locations south of 51° N latitude, but was not different from the early seeding dates at sites north of 51° N latitude. The greatest growing system stability, based on high grain yield and low variability in grain yield, was observed from plantings at 2°C and 4°C soil temperatures. Studies conducted in the Australian grain belt evaluating early seeding have reported grain yield increases as a result of better establishment, deeper rooting, increased access to soil moisture, sustained vegetative growth periods and reduced heat during flowering and grain fill (Hunt et al. 2018, Kirkegaard et al. 2015). Successful establishment of wheat in an ultra-early seeding system on the northern Great Plains may have the potential to increase yield compared to current practices, and may provide long term benefits by avoiding grain yield loss due to reduced precipitation and increased temperatures during grain fill, impacts commonly predicted as a result of climate change.

The present study's objective was to evaluate the responses of grain yield and grain quality to manipulations in agronomic management practices in an ultra-early wheat seeding system in the western Canadian region of the northern Great Plains. Four plantings based on soil temperature triggers initiated at 0 - 2.5°C were evaluated in combination with cold-tolerant spring wheat genetics, sowing density and depth manipulations, to determine if ultra-early seeding systems coupled with optimized agronomic practices could provide a grain yield advantage over current seeding practices.

3.2 Materials and methods

3.2.1 Site description, experimental design, and determination of planting time using soil temperature triggers

This study was conducted at six sites in western Canada over 4 years from 2015-2018, resulting in 13 total site-years (Figure 3-1, Table 3-1). The treatment structure consisted of a factorial randomized complete block arrangement with 32 total treatments resulting from combinations of four planting times, two wheat lines, two planting rates, and two planting depths. Each trial contained four replicates. The planting times were based on soil temperature triggers of 0 - 2.5, 5, 7.5 and 10°C as measured with an Omega^{TM} TPD42 soil temperature probe at 5 cm depth at 10:00 AM each day prior to seeding. If soil conditions made seeding impossible at the first soil temperature trigger (0 - 2.5°C) each seeding date was adjusted so that there was a 2.5°C temperature difference between each remaining seeding date. Sites located in southern Alberta and Saskatchewan were generally able to seed at 0 – 2.5°C soil temperatures. In some cases, sites in central and northern Alberta were unable to seed at the earliest soil temperature trigger due to excess moisture and saturated soils; in these cases, seeding occurred as early as equipment could access field sites.

The wheat lines used were two experimental lines selected for spring growth habit and improved cold tolerance as previously described in Collier et al. (2020). These lines, 'LQ1299A' and 'LQ1315A', were developed by intercrossing two previously identified cold tolerant spring wheat lines derived from a cross between 'Norstar' Canada Western Red Winter (CWRW) wheat and 'Bergen,' a Dark Northern Spring (DNS) wheat commonly grown in North Dakota and developed in the United States of America (Table 3-2) (Grant 1980).

Two sowing densities were used to represent sub-optimal (200 seeds m^{-2}) and optimal (400 seeds m^{-2}) wheat seeding rates. Germination tests were performed and used to standardize treatments at 200 and 400 viable seeds m^{-2} respectively. Seeding depths of 2.5 and 5 cm were used to approximate the upper and lower ranges of standard wheat seeding depths in western Canada.

3.2.2 Seeding operations, nutrient management, and pest management

Seeding equipment varied between sites but remained similar to the drill designed and built by Agriculture and Agri-Food Canada Lethbridge, which utilized ConservaPak^{TM} knife openers (8) (Model CP129, ConservaPak, Indian Head, SK, Canada) spaced at 24 cm apart, a Valmar^{TM} air product delivery system (Valmar Air Inc., Elie, MB, Canada), a Raven^{TM} hydraulic seed calibration and product control system (Raven Industries Inc. Sioux Falls, SD, USA) and Morris^{TM} seed cups (Morris Industries Ltd. Saskatoon, SK, Canada). Macronutrient fertilizer (N, P, K, S) was applied based on soil test recommendations and yield goals appropriate to each site (Western Ag Labs PRS® soil test system, Saskatoon, SK, Canada). If required, applied fertilizer forms were: urea nitrogen (46-0-0-0), monoammonium phosphate (11-52-0-0) (Koch Fertilizer, LLC. Wichita, KS, USA), potassium chloride (0-0-60) (The Mosaic Company, Tampa FL, USA), and ammonium sulphate (21-0-0-24) (Yara Canada, Regina, SK, Canada). Fertilizer granules were incorporated as a band below and to the side of the seed row at seeding. All seed was treated with a fungicide seed treatment to control common seedling diseases (Raxil PRO – Tebuconazole [(RS)-1-p-chlorophenyl-4,4-dimethyl-3-(1H-1,2,4-triazol-1-ylmethyl)pentan-3-ol] 3.0 g L^{-1} + prothioconazole [(RS)-2-[2-(1-chlorocyclopropyl)-3-(2-chlorophenyl)-2-hydroxypropyl]-2,4-dihydro-1,2,4-triazole-3-thione] 15.4 g L^{-1} + metalaxyl [metyl N-(methocyacetyl)-N-2,6-xylyl-DL-alanite] 6.2 g L^{-1} [Bayer CropScience Canada Inc., Calgary, AB]). Plots were uniformly seeded directly into the previous crop stubble at target seeding rates across the desired length plus 50 cm on either end. The front and back of each two to four meter wide plot was then trimmed or rototilled to provide the desired plot length (6m to 8m depending on trial location) and avoid any effect of engaging or disengaging seeding equipment. The immediately preceding crop at all sites was either canola (*Brassica napus L.*), chem-fallow, or barley silage (*Hordeum vulgare L.*); no trials were seeded into wheat stubble. Seeding depth was adjusted as needed for each plot using appropriate spacers to accurately provide the two seeding depths evaluated.

Weed control was achieved using in-crop herbicide applications made from Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie (BBCH) scale 12-22, generally in late-May. As there was growth stage variation within replications due to planting date variation, herbicide products with restrictive crop staging, residual properties or auxin type active ingredients were not used. Herbicide selection was limited to herbicides or combinations of herbicides from the Weed Science Society of America (WSSA) groups 2, 6, and 27 (Shaner 2014). All post-emergent herbicide applications were made using motorized sprayers calibrated to deliver a carrier volume of 45 L ha^{-1} at 275 kPa pressure.

3.2.3 Data collection

Days to emergence was determined when 50% of the plants in a plot had emerged. Crop anthesis was recorded in days from planting date when 50% of the heads in a plot first extruded anthers, and maturity was assessed at physiological maturity, when kernel moisture content in the lower third of a head contained less than 40% moisture content. The period from emergence to maturity was broken down into segments from emergence to anthesis, anthesis to maturity and emergence to maturity, all measured and reported in days. This removed the influence of longer planting to emergence periods experienced by the early seeded treatments and avoided potentially false conclusions regarding the effects of ultra-early planting on the length of vegetative and reproductive growth periods of wheat. Leaf area index (LAI) at the Lethbridge, Alberta sites was recorded using an AccuPAR LP 80 Ceptometer (Decagon Devices, Pullman, WA, USA) placed between rows with measurements recorded above and below the canopy at solar noon (Gower et al. 1999, Jonckheere et al. 2003). LAI measurements were taken four times from June 1 to July 1 to capture leaf area prior to and during the summer solstice. Growing degree-days base 0°C (GDD B_0) at the Lethbridge, Alberta sites for each season (2015-2018) were recorded and calculated using the Government of Alberta, Alberta Climate Information System (ACIS 2020). Plant counts for each plot were completed from BBCH 20 to BBCH 49 to indicate total viable plants in two one-m long areas of the second and third rows as well as second and third last rows of each plot. The lengths of row used for plant counts were marked and used later in the growing season to count the number of heads m^{-2}. Heads $plant^{-1}$ was calculated using the number of heads divided by the plant count for each staked section of row. Plant height was recorded from two randomly selected but representative areas of each plot, measuring the height of five main spikes, excluding awns.

Each plot was harvested in its entirety with a Wintersteiger Nurserymaster Elite (Wintersteiger AG Salt Lake City, Utah, USA) or similar plot combine equipped with a straight cut header, pickup reel and crop lifters. Grain yield for each plot was weighed after samples were dried and corrected to 14% grain moisture content and was used to calculate total grain yield per ha (Mg ha^{-1}). A 2 kg subsample of grain was retained to determine seed mass (from 500 kernels) and grain bulk density (kg hL^{-1}). Near infrared reflectance spectroscopy technology was used to determine whole grain protein concentration from the same subsample (Foss Decater GrainSpec, Foss Food Technology Inc., Eden Prairie, MN) (Irvine et al. 2013).

3.2.4 Statistical analyses

The MIXED procedure of SAS was used to analyze collected data, and any outlier observations detected by tests for normality using PROC UNIVARIATE were removed before completing a combined analysis over all years and environments (site-years). The combined analysis of variance was completed using site-year, replication, soil temperature at seeding, wheat line, seeding rate and seeding depth as variables in the CLASS statement (SAS Institute 2009; Littell et al. 2006). Error variances were heterogenous among environments, and corrected Akaike's information criterion (AICc) regarding model fit indicated that modelling residual variance heterogeneity resulted in improved fit. Variance heterogeneity was modelled using the RANDOM statement in PROC MIXED with the group option set to environment and the Satterthwaite approximation for degrees of freedom. Environment and the interactions associated with environment were considered random effects, while treatment effects were considered fixed and significant when $P \leq 0.05$ (Steel et al. 1997). Contrast statements were used in the MIXED procedure to determine linear and quadratic relationships of planting date and response variables as well as differences in LAI between groupings of planting dates and seeding rates.

The effect of planting date on yield was evaluated using an analysis of covariance (ANCOVA) as described by Yang and Juskiw (2011). The use of ANCOVA reduced the error mean square, accounted for missing data, and increased the precision of the resulting regression analysis. Planting date was used as a covariate and classification variable by generating a second column of data identical to the planting date to be used as the covariate. Type I sums of squares was specified with the METHOD statement in PROC MIXED (Yang and Juskiw, 2011). Direct regression variables (covariates) s and s*s represented linear and quadratic responses to planting date and were part of the MODEL statement. Environment or group interactions with s and s*s are used to evaluate linear and quadratic responses that are heterogeneous compared to planting date. A significant negative linear regression was indicated and used to represent grain yield decline with delayed planting.

A biplot grouping methodology originally described by Francis and Kannenberg (1978) was modified and used to explore system stability and the variability of wheat yield. The methodology proposed by Döring and Reckling (2018) was used to generate an adjusted coefficient of variation (aCV) for use in place of the standard coefficient of variation (CV) employed by Francis and Kannenberg (1978). The subsequent use of aCV in the place of CV on biplot horizontal axes accounts for the impact of yield data conforming to Taylor's Power Law where the CV value is dependent on the yield and will tend to decrease relative to yield increases (Taylor 1961, Döring 2015). The aCV and means across years and replications were estimated for each treatment combination. Means were then plotted on the vertical axis against the aCV on the horizontal axis and used to categorize the data into four groups/quadrants: (Group I) high mean grain yield and low variability, (Group II) high mean grain yield and high variability, (Group III) low mean grain yield and high variability, and (Group IV) low mean grain yield and low variability.

3.3 Results

3.3.1 Environmental conditions

Environmental conditions varied between locations, and years at each location. The earliest planting was in 2016 in Lethbridge, when the initial soil temperature trigger was satisfied, and planting occurred on February 16. In the same year, the first seeding date at the Dawson Creek location was not until April 21, a differential of 64 days. This difference in initial seeding date was due to geographic location and variation in weather and winter thaw patterns between sites (Figure 3-1). The following year the initial planting at Lethbridge was not triggered until March 20, 32 days later than the year before. The date of initial soil temperature trigger satisfaction and first planting is listed in Table 3-1 for each location and year. In general, the initial planting date occurred prior to the accumulation of 5% of seasonal GDD B_0. GDD B_0 accumulation at the Lethbridge, Alberta was zero at initial planting in 2015 and 2016, 1.1% in 2017, and 4.4% in 2018 (Figure 3-2).

Precipitation events over the course of the study also varied between years and locations. Accumulated precipitation in 2015 was below average at all trial locations. Precipitation in 2016 was above 30-year averages for all trial locations except Lethbridge, Alberta which was 11% below the 30-year average. In 2017 and 2018 all sites received below average precipitation (Table 3-1).

All sites recorded ambient air temperatures below 0°C after seeding, with the exception of Edmonton, Alberta in 2017. Eight of 13 sites recorded air temperatures below -5.0°C after the initial seeding date; the most severe observations were -10.2°C at Lethbridge, Alberta in 2016 and -9.8°C in Scott, Saskatchewan in 2016. Several locations recorded air temperatures below 0°C for multiple nights after initial planting. Eleven of 13 sites recorded more than ten nights with air temperatures below 0°C. In 2015 and 2016, Lethbridge, Alberta had 37 and 36 nights respectively with ambient air temperatures below 0°C after initial planting occurred. In 2016 and 2017, Scott, Saskatchewan had 21 and 27 nights respectively with ambient air temperatures below 0°C after initial planting (Table 3-1).

3.3.2 Grain yield, grain quality, and yield components

Grain yield was greatest at the earliest planting dates. The latest planting date, corresponding to a soil temperature trigger of 10°C, resulted in reduced grain yield relative to each of the three earlier planting dates (Table 3-3). Grain yield from the earliest to the latest seeding date decreased linearly by 0.38 Mg ha^{-1} (Table 3-3). The optimum seeding rate of 400 seeds m^{-2} resulted in greater grain yield than the 200 seeds m^{-2} seeding rate (Table 3-3). Grain yield decrease from the earliest to latest seeding date was greater at the sub-optimal seeding rate of 200 seeds m^{-2} than at the optimal seeding rate of 400 seeds m^{-2} (Figure 3-3). The optimum seeding rate resulted in a 0.26 Mg ha^{-1} greater grain yield than the sub-optimal seeding rate. Seeding depth and wheat line did not significantly affect grain yield.

Delayed planting resulted in a linear increase in grain protein concentration, which corresponded to a concurrent linear decrease in grain yield (Table 3-3, Figure 3-3). Similarly, increased seeding rates resulted in reduced grain protein concentration, but greater overall grain yield (Table 3-3). Grain protein concentration increased by 0.3% from the earliest to latest planting date, and by 0.1% from the optimum to low seeding rates. There was also a minor difference in grain protein concentration between wheat lines, as 'LQ1299A' had a 0.1% higher grain protein concentration than 'LQ1315A'. Seeding depth showed no significant effect on grain protein concentration (Table 3-3).

Thousand kernel weight and grain test weight were most affected by seeding rate. The optimum seeding rate resulted in a 0.5 kg hL^{-1} increase in test weight and a corresponding 0.3 g decrease in thousand kernel weight (Table 3-3). Planting date and seeding depth had no effect on test weight, however, thousand kernel weight increased linearly from the earliest to latest plantings and increased at the deeper seeding depth (Table 3-3). 'LQ1315A' exhibited a greater seed test weight than 'LQ1299A'.

Plant height was not affected by any treatment with the exception of wheat line; 'LQ1315A' was one cm taller than 'LQ1299A'. Initial plant counts were lower for the last two planting dates relative to the second planting date. Plant counts for the first planting date were not different from the second, third or fourth planting dates. Wheat line 'LQ1315A', the lower planting rate, and the deeper planting depth resulted in lower plant counts. Tillering, or heads $plant^{-1}$, was not significantly affected by any treatment, however heads m^{-2} was decreased with delayed seeding. The last two planting dates had fewer heads m^{-2} than the first two planting dates (Table 3-3). Lower planting rates and deeper planting also led to reduced numbers of heads m^{-2} (Table 3-3). The only significant interactions for grain yield, grain quality, and yield component parameters was the presence of a significant wheat line × seeding rate interaction for plant height and heads $plant^{-1}$. At the higher planting rate 'LQ1315A' was slightly shorter and produced relatively fewer heads $plant^{-1}$ than at the lower planting rate.

3.3.3 Crop development

Earlier plantings emerged slowly, which increased the total length of time for these treatments to reach anthesis and to reach maturity. A similar effect was observed by Collier et al. (2020) where the earliest plantings into cool soils took longer to emerge. As such, the growth period was broken down into segments from emergence to anthesis, anthesis to maturity and emergence to maturity to remove any confounding impacts of slow emergence on growth period lengths (Table 3-4). The earliest planting required 124.7 days to reach maturity while the latest planting only required 104.7 days. The 20 day differential in maturity is a combination of the earlier planting requiring 14.0 more days to emerge than the later planted treatment, combined with longer periods from emergence to anthesis and from anthesis to maturity for the earlier planted treatments. The earliest planted treatments had vegetative growth periods up to three days longer, and grain fill periods up four days longer than the latest planted treatments. Based on the four-year average GDD B_0 accumulation at the Lethbridge, Alberta site during the course of this study the extra length of the vegetative and grain-filling periods would allow the utilization of up to an additional 140 GDD B_0 for the earliest planting date relative to the latest planting date.

The LAI measurements were initially greater for plantings triggered by 0 - 2.5°C, 5°C, and 7.5°C soil temperatures than the 10°C triggered planting (Figure 3-4). The differential in LAI between planting times decreased and was not significantly different at the second to fourth ratings. Similarly, LAI was greater at the optimum seeding rate for the first two LAI evaluations with no difference at the third and fourth ratings (Figure 3-5). Thus, prior to the summer solstice on June 21, the treatments seeded at 10°C soil temperatures and those seeded at the sub-optimal seeding rate were able to achieve LAI values similar to the earlier planting dates and optimal seeding rate treatments; however, 42% - 45% of the total growing season GDD B_0 had already accumulated by this date (Figure 3-4, Figure 3-5).

The optimum seeding rate shortened days to emergence, and subsequent days to maturity were decreased by one day at the optimum seeding rate. A corresponding increase in the length of the emergence to anthesis period and a one day decrease in the length of the anthesis to maturity period at the optimum seeding rates resulted in no significant difference in the emergence to maturity period based on seeding rate. Deeper seeding depths increased days to emergence, anthesis and maturity, but did not have any effect on the length of the growth periods. Similarly, the wheat lines differed in the speed with which they emerged and reached anthesis, but this did not have an effect on the vegetative, reproductive, or total growth periods represented by the emergence to anthesis, anthesis to maturity, and emergence to maturity growth segments.

3.3.4 Grain yield stability

To visualize the stability of an ultra-early wheat seeding system, including optimized agronomics, we employed a version of the Francis and Kannenberg (1978) bi-plot grouping method modified to include aCV values to remove dependence of system stability on grain yield (Figure 3-6) (Döring and Reckling, 2018). All combinations of seeding rate, seeding depth, and planting time are captured by sixteen points on each biplot based on the mean grain yield and aCV for each wheat line across years and replications. Data was categorized into four quadrants: (Group I) high mean grain yield and low variability, (Group II) high mean grain yield and high variability, (Group III) low mean grain yield and high variability, and (Group IV) low mean grain yield and low variability.

The modified Francis and Kannenberg (1978) biplots in Figure 3-6 show that all data points associated with the latest planting time (based on a soil temperature planting trigger of 10°C) are located in Groups III and IV, indicating a low mean grain yield. Group I, which is defined by the greatest grain yield and least variability in grain yield, contains ten points in total (31% of all possible treatment combinations). Of these points, 50% represent the earliest planting date (0 – 2.5°C soil temperature trigger), while the second and third planting dates (5°C and 7.5°C soil temperature triggers) are represented by 30% and 20% of the data points in Group I respectively. The optimum seeding rate is represented by 90% of the points in Group I. Both seeding depths are equally represented in Group I, however the average aCV of data points associated with shallow seeding is lower than the average aCV of treatments associated with deep seeding. There are 12 data points in the least stable groups, Groups II and III (38% of all possible treatment combinations). Of the data points in Groups II and III, 17% are from the latest planting date, 50% from the deep seeding depth, and 67% are from the low seeding rate. The lowest yielding groups, Groups III and IV, contain 14 data points (44% of all possible treatment combinations). Of the data points in Groups III and IV, 57% are from the latest seeding date, 50% from the deep seeding depth, and 71% are from the low seeding rate. The greatest grain yield stability indicated in Figure 3-6 comes from combinations including the optimum seeding rate, early planting, and to a lesser extent, shallow seeding depth.

3.4 Discussion

3.4.1 Soil temperature based planting

The large variation in environmental conditions observed in this study is typical on the northern Great Plains and justifies a management system based on soil temperature to initiate planting rather than one dependent on arbitrary calendar date (Collier et al. 2020; Shen et al. 2005). Shen et al. (2005) defined the beginning of the growing season in Alberta, Canada as the first day of the year when five consecutive days have an average mean ambient air temperature of 5°C, and the end of the growing season as the first day in the fall when the mean ambient air temperature is below 5°C. No long-term trends for the start of the growing season, the length of the growing season, or the end of the growing season in Alberta were identified, though an increase in the frost-free period due to earlier final spring frosts and later first fall frosts from 1901 to 2002 was reported (Shen et al. 2005). Thus, producers may generally begin seeding earlier, however, when seeding can safely begin occurs at a different time each year. Using soil temperature triggers to initiate seeding can standardize the start of seeding with environmental conditions from year to year more effectively than relying on calendar date. Soil temperature-based planting can also standardize planting across substantial distances within regions. Sites south of 51° N latitude can often access fields to begin planting earlier than planting is actually initiated, as producers tend to wait for certain calendar dates or a long-term forecast that indicates air temperatures below 0°C are unlikely. The temperature buffering capacity of soils that have reached 0°C or higher has shown to provide adequate protection from freezing temperatures for the sowing of spring wheat, thus providing a reliable indicator for safely initiating seeding on the northern Great Plains (Collier et al. 2020). Sites on the northern Great Plains north of 51° N latitude tended to take longer to reach soil temperatures of 0°C. However, once the darker soils north of 51° N latitude reached 0°C, they tended to warm to 10°C in fewer days than the lighter brown soils located south of 51° N latitude (Figure 3-1). Thus, the time elapsed between triggering the first and last planting based on soil temperature was greater at southern trial locations than at northern trial locations. This can be attributed to later snow cover ablation, greater water holding capacity, and greater solar energy absorption by the darker grey wooded luvisols, orthic black chernozems, and orthic dark brown chernozems primarily found north of 51° N latitude compared to the dark brown and brown chernozem soils primarily found south of 51° N latitude (Figure 3-1) (Collier et al. 2020; Zhao et al. 2002). The short window to benefit from ultra-early seeding in the more northern areas of the northern Great Plains region necessitates a simple, low cost, reliable system of confirming when planting can safely begin.

3.4.2 Grain yield response to ultra-early wheat seeding systems

A previous study completed by Collier et al. (2020) compared three cold tolerant wheat lines, including the two wheat lines used in the present study, 'LQ1299A', and 'LQ1315A', to a Canada Western Red Spring (CWRS) wheat variety 'AC Stettler' described by DePauw et al. (2009). The study reported no detrimental grain yield effect of ultra-early seeding and no difference in growing system stability between conventional or cold tolerant wheat genetics in an ultra-early seeding system. Ultra-early seeding may not allow enough time for cold tolerant lines to fully acclimate to cold conditions, thus reducing their potential benefit to the system (Fowler et al. 2008). The present study builds on the results of Collier et al. (2020) by incorporating agronomic management variables into ultra-early seeding systems. Increased grain yield and growing system stability was realized by using optimized agronomics. Combinations of the earliest planting dates, higher planting rate and, to a lesser extent, a shallow planting depth resulted in the greatest grain yield and greatest system stability (Figure 3-6). The greater grain yield from earlier planting is a result of multiple factors including plant survival equivalent or superior to later planted treatments, combined with an increased number of heads m^{-2} at the earlier plantings, and longer vegetative growth and grain fill periods. Shifting seeding earlier resulted in plants that were more physiologically advanced earlier in the growing season. The presence of greater leaf area earlier in the growing season for ultra-early seeded treatments and treatments planted at the optimum seeding rate improved their ability to utilize growing degree days accumulated prior to the summer solstice (Figure 3-4, Figure 3-5). At the Lethbridge, Alberta site from 2015-2018, 42% - 45% of the total growing season GDD B_0 accumulated prior to the summer solstice. Earlier seeded plants could more effectively take advantage of solar radiation during the long daylight hours leading up to the summer solstice, due to increased vegetative and root biomass accumulation and increased transpiration efficiency under the relatively cooler conditions, similar to the results reported by Porker et al. (2020). Additionally, these plants progressed to reproductive growth and grain fill earlier in the season than the later seeded plants, enabling more complete tiller viability and a greater proportion of grain fill to occur in early and mid-July during days with more daylight hours (Table 3-4). Earlier initiation of grain fill avoided heat stress and drought which commonly occur in late July and August on the northern Great Plains (Farooq et al. 2011). Increased temperatures during grain-filling and reduced, or more sporadic, precipitation during the growing season are identified as main factors in predicted reductions in wheat grain yield on the northern Great Plains by 2050 (Asseng et al. 2019; He et al. 2012; Lanning et al. 2010; Asseng et al. 2004).

Similar avoidance strategies have been studied in the Mediterranean climates of Australia and the United States Pacific Northwest where wheat grain yield is limited due to heat and soil moisture availability (Cann et al. 2020; Porker et al. 2020). Adoption of winter growth habit wheat cultivars and adjusting seeding to earlier dates in both regions was associated with significant grain yield benefit attributed to longer vegetative growth phases, increased root development and depth, increased transpiration efficiency, subsoil moisture availability and avoidance of heat stress at grain fill (Cann et al. 2020, Hunt et al. 2019). The implementation of a similar ultra-early seeding system for spring wheat on the northern Great Plains in response to increases in growing season temperature and reductions in growing season precipitation can serve as a mechanism to reduce future yield loss. The results of the present study indicate there is also an immediate benefit to grain yield and growing system stability by moving to an ultra-early seeding system (Figure 3-6). Earlier seeding can be easily implemented on the northern Great Plains to take advantage of early season soil moisture, increase early season LAI and utilization of GDD accumulated prior to the summer solstice, and avoid late season heat stress. This study indicates planting spring wheat as soon as soil temperatures exceed 0°C can increase grain yield by as much as 6.8% over wheat planted at 10°C soil temperatures. The negative linear association we observed between wheat grain yield and planting date suggests a soil temperature increase of 2.5°C may cause a 0.13 Mg ha^{-1} decrease in realized grain yield. Moreover, the magnitude of decrease may increase with time as increasing growing season temperatures negatively impact wheat production on the northern Great Plains.

The calendar date of May 1 corresponds to traditional spring wheat planting at Lethbridge, Alberta. Recorded soil temperatures from the ACIS station at the Lethbridge Research and Development Centre, Agriculture and Agri-food Canada on May 1 in 2015, 2016, and 2017 (2018 data not available) were used to generate a three year average PD value to insert in the linear regression equations for grain yield developed in this study (Figure 3-3) (ACIS 2020). By delaying planting to May 1 an average of 14.1% of the total GDD B_0 accumulation for the growing season would have elapsed prior to planting, accounting for 339 GDD B_0. Grain yield from a planting date of May 1 at a planting rate of 200 seeds m^{-2} is predicted to be 4.20 Mg ha^{-1}, a decrease of 0.63 Mg ha^{-1}, or 15%, relative to the grain yield expected from planting at 0 - 2.5°C at 200 seeds m^{-2}. At a planting rate of 400 seeds m^{-2} and planting date of May 1, the predicted grain yield is 4.53 Mg ha^{-1}, a decrease of 0.51 Mg ha^{-1}, or 11%, relative to the grain yield expected from planting at 0 - 2.5°C and 400 seeds m^{-2}. Using an average wheat grain value of \$246.00 Mg^{-1} (September 2015 to December 2019 average southern Alberta price for CWRS wheat, 13.5% protein content (Alberta Wheat Commission 2020)) seeding ultra-early at 0 – 2.5°C soil temperatures and planting at the optimum seeding rate of 400 seeds m^{-2} would result in a gross economic benefit to the grower of \$206.64 ha^{-1} relative to delaying seeding to May 1 and using a lower planting density of 200 seeds m^{-2}. Current crop insurance standards in western Canada dictate that field crops must be planted by a set date to be viable and thus, be compensable in the event of crop failure. This date sets a de facto limit on how late into the growing season crops can be sown successfully. This study reports a significant yield penalty for delayed planting of wheat; in addition to providing increased yield and economic benefit to the grower, an ultra-early wheat growing system provides a basis for insurance providers to incentivize earlier planting.

3.4.3 Agronomic management of ultra-early wheat seeding systems

A modern and innovative cropping system is composed of interwoven G × E × M interactions where G is genotype, E is environment and M is crop management (Beres et al. 2020). In the hypothesized ultra-early wheat seeding system, the requirement for a specific cold tolerant genotype was not apparent in the Collier et al. (2020) study. Thus, in its current state, ultra-early wheat systems tend to be optimized through management factors. This is not to say genetics be overlooked, but the reality is that wheat lines selected and bred in the northern latitudes of North America likely evolved by expressing tolerance to abiotic pressure related to cold soils (E). Improvements over conventional genetics may be needed if dormant-seeding in late-fall or winter was adopted as opposed to late-winter or spring, which would necessitate the consideration for a ‘flex wheat’ that would possess traits designed intentionally for an ultra-early seeding system.

Crop management strategies for reducing the impact of environment on ultra-early wheat seeding systems should reduce abiotic and/or biotic stresses and increase grain yield and growing system stability, thereby moving the growing system closer to achieving potential yield (Fischer 2015). A systems-based approach focused on managing G × E × M interactions has been shown to improve grain yield and resiliency. Kirkegaard and Hunt (2010) implemented a systems-based management approach accounting for wheat genetics, agronomic management and environmental variation in a wheat cropping system and demonstrated the ability to increase growing system stability and yield potential by three times. In this approach the total yield benefit was greater than the sum of the individual components indicating a synergistic effect of successful G × E × M management. Growing systems designed to capitalize on G × E × M interactions can maintain current yield potential in the presence of adverse environmental effects, and result in increased grain yield and increased growing system sustainability providing an avenue for future intensification (Beres et al. 2020a, Cassman and Grassini 2020, Fischer and Conner 2018). In the proposed management of ultra-early wheat growing systems, high performing spring wheat cultivars already available to growers combined with optimal seeding rates and shallow seeding depths can be further combined with additional management strategies to limit negative effects of abiotic stress early in the growing season. For example, previous studies have reported on the beneficial effects of fungicidal and dual fungicidal/insecticidal seed treatments to reduce abiotic stress, disease and insect pressure, and increase plant stand and grain yield in cereals (Beres et al. 2016; Turkington et al. 2016; Ford et al. 2010). This study included a fungicidal seed treatment to reduce seed and soil borne diseases as confounding effects. Cold wet soils at planting, extended periods from planting to emergence, and observed reduced emergence from deeper seeded treatments suggest effective seed treatments should be considered an integral part of abiotic and biotic stress management for optimized ultra-early wheat seeding systems.

Optimizing the planting rate increased grain yield and grain yield stability in ultra-early seeding. The optimum planting rate used in this study (400 seeds m^{-2}) increased grain yield by 5.5% over the lower planting rate, and was the variable most strongly tied to increased system stability

(Table 3-3, Figure 3-6). The optimum planting rate increased the number of plants and leaf area per unit area despite having a greater mortality than the low planting rate treatments. The ability to withstand mortality and maintain a suitable plant stand is an important yield stabilizing characteristic of using optimum planting rates in an ultra-early wheat seeding system. Increased grain yield from both the optimum planting rate and earlier planting resulted in minor decreases in grain protein concentration, however, the increase in grain yield resulted in greater total protein production per unit area.

Reduced survival for plants seeded at 5 cm depth compared to those seeded at 2.5 cm was indicated by a significant decrease in initial plant counts and heads m^{-2} (Table 3-3). This may be attributed to a combination of delayed emergence and reduced vigor, resulting from stressful growing conditions and extensive use of seed carbohydrate reserves. Semi-dwarf hexaploid wheats including ‘LQ1299A’ and ‘LQ1315A’ tend to have reduced coleoptile length relative to conventional height wheats (Pandey et al. 2015; Ellis et al. 2004). Reduced coleoptile length, combined with reduced vigor at emergence due to deeper seeding, may account for reduced plant survival. While no grain yield penalty was observed for planting at a 5 cm depth, the reduction in plant stand and minor observed increase in aCV at 5 cm depth versus 2.5 cm depth indicate overall yield potential may be negatively impacted by deep seeding. This impact may be more prominent when abiotic or biotic stresses result in increased mortality during the growing season. This recommendation differs from that of Cann et al. (2020) primarily due to the availability of soil moisture after spring snow melt on the northern Great Plains.

3.4.4 Producer level implementation

Producer implementation of ultra-early wheat seeding on the northern Great Plains requires relatively minor adjustments to current management practices. Collier et al. (2020) reported maximum wheat grain yield was realized when planting occurred prior to soils reaching 3.9°C. The results of the present study corroborate this conclusion and indicate the ideal seeding window is between soil temperatures of 0 and 7.5°C. Producers in the southern region of the northern Great Plains have the opportunity to adopt ultra-early seeding across larger regions as slower warming of the soil and less snow cover allow more area to be sown prior to reaching 7.5°C soil temperatures. In the northern areas of the northern Great Plains producers may have to select fields based on drainage and accessibility in the early spring in order to successfully implement ultra-early seeding where it is best suited to their farm. Significant management and equipment adjustments are not required; however, consideration may be given to equipment that limits compaction, residual herbicide systems that can be applied in the fall as ultra-early seeding will preclude a spring pre-seed herbicide application, and fertilizer applications in the fall that can reduce downtime during spring planting. Producers should use optimum seeding rates of not less than 400 seeds m^{-2}, and higher if seed quality is sub-optimal or variety specific optimum seeding rate data is available. A shallow seeding depth of 2.5 cm decreased time to emergence and increased plant stand. Combined with ample spring moisture at ultra-early seeding times, shallow seeding can help maintain growing system stability.

3.5 Conclusions

Wheat grain yield and growing system stability can be increased by moving wheat planting earlier in the year on the northern Great Plains. Ideal planting time can be determined using a soil temperature trigger-based seeding system, and seeding can begin as soon as is feasible after 0°C soil temperatures are reached. Ultra-early wheat seeding systems can be optimized by using seeding rates of 400 seeds m^{-2} or higher, which increases grain yield and decreases grain yield variability, thus increasing overall growing system stability. Seeding depth did not have a direct affect on grain yield, however shallow seeding resulted in increased plant populations and maintained growing system stability. A delay in wheat plantings i.e. soil temperatures ≥ 7.5°C to 10°C will introduce greater yield instability and inferior yield attainment well below potential. For example, through the duration of this study, if planting wheat on May 1 in Lethbridge, Alberta when the average soil temperature was 13.6°C as opposed to planting based on a soil temperature trigger of 0-2.5°C, a grower would experience a loss in gross revenue of approximately \$206 ha^{-1}.

Future adoption of ultra-early seeding may be necessary due to climate driven increases in average growing season temperature and either decreases in, or changes to, precipitation patterns. Similar environmental factors constraining grain yield are currently faced in Australia and the United States Pacific Northwest where similar early-sowing approaches are being evaluated to improve G × E × M synergies. Future work in western Canada will evaluate weed management and fertility programs for ultra-early wheat seeding systems, as well as evaluate multiple classes of conventional western Canadian wheat and durum wheat for adaptation to ultra-early seeding systems.

3.6 Acknowledgements

Thank you to the staff at Agriculture and Agri-Food Canada Lethbridge (Ryan Dyck, Steve Simmill, Warren Taylor, and many seasonal staff); Agriculture and Agri-Food Canada Scott (Cindy Gampe and Arlen Kapiniak); the staff at the University of Alberta Klaus Strenzke, Muhammad Iqbal, Fabiana Dias, Joseph Moss, Tom Keady, Katherine Chabot, and Russell Puk); the British Columbia Grain Producers Association; and many supporters at each trial location. Thanks to Craig Stevenson, and Rong-Cai Yang for statistical analyses support and Erin Collier for manuscript editing. Funding for this study was provided by the Agricultural Funding Consortium with funds provided by the Alberta Wheat Commission, the Western Grains Research Foundation and Alberta Innovates BioSolutions, grant number 2014F172R.

3.7 Tables

Table 3-1. Agroecological data, precipitation, post-seeding air temperature extremes and cumulative freezing events recorded at each location × year.

Location	Latitude/Longitude	Agroecological Region	Soil Zone	Average Yearly Precipitation* (mm)	Year	Actual Precipitation (mm)	Earliest Seeding Date**	Number of days with air temperature below 0°C after initial seeding date	Lowest air temperature recorded after seeding (°C)
Dawson Creek, BC	55°48’N 120°14’W	Parkland	Grey Wooded	453	2015	325	April 16	12	-5.0
					2016	542	April 21	11	-6.1
Edmonton, AB	53°33’N 113°29’W	Parkland	Black	446	2015	299	April 9	12	-4.2
					2016	510	March 29	11	-3.6
					2017	416	May 5	0	2.3
Lethbridge, AB	49°41’N 112°50’W	Western Prairies	Dark Brown	380	2015	251	March 6	37	-6.7
					2016	338	February 16	36	-10.2
					2017	249	March 20	17	-7.6
					2018	284	April 23	2	-1.2
Regina, SK	50°26’N 104°35’W	Western Prairies	Dark Brown	397	2015	347	April 21	11	-5.0
Scott, SK	52°21’N 108°49’W	Western Prairies	Dark Brown	366	2016	415	April 2	21	-9.8
					2017	300	March 31	27	-9.4
Swift Current, SK	50°18’N 107°46’W	Western Prairies	Brown	357	2015	304	April 10	23	-6.4

* 1981-2010 average yearly precipitation accumulation. ** Based on 0 - 2.5°C soil temperature trigger date. Initial planting at Dawson Creek, BC in 2015 and 2016, and Edmonton, AB in 2015 occurred after soil temperatures reached 2.5°C, but prior to soils reaching 4°C. Planting delays were due to inaccessibility of trial sites early in the season. In these cases, each successive planting date was delayed so that a differential of 2.5°C in soil temperature between each planting date was maintained.

Table 3-2. Classification of cold tolerant lines, and parent wheat lines.

Line	Parental Lines	Parental Lines Canadian wheat Classification	Experimental Designation	Reference
LQ1299A[Ɨ]	Norstar/Bergen	CWRW[Ŧ]/DNS[β]	Cold Tolerant[¥]	Larsen 2012
LQ1315A[Ɨ]	Norstar/Bergen	CWRW/DNS	Cold Tolerant	Larsen 2012

(¥) Cold tolerant lines were selected from 92 double haploid lines from a Norstar/Bergen cross initially completed at AAFC Lethbridge. Cold tolerant lines were selected based on spring growth habit, demonstrated cold tolerance using LT_{50} tests, and yield and quality parameters (Collier et al. 2020, Larson 2012).

(Ŧ) Canada Western Red Winter

(β) Dark Northern Spring (United States of America hard red spring wheat class)

(Ɨ) Undetermined Classification

Table 3-3. Least square means for grain yield, grain quality, and select agronomic parameters affected by ultra-early planting.

	Yield (Mg ha^{-1})	**Protein (%)**	**Test Weight (kg hL^{-1})**	**Thousand Kernel Weight (g)**	**Height (cm)**	**Plants m^{-2} [¥]**	**Heads m^{-2} [¥]**	**Heads plant^{-1} [¥]**
Planting Date (PD)[Ŧ]								
1 (Earliest)	4.95	11.9	77.2	34.1	78	200	390	2.2
2	4.93	12.0	77.4	34.0	78	214	383	2.0
3	4.84	12.1	77.5	34.2	77	198	361	2.0
4 (Latest)	4.57	12.2	77.3	34.5	78	192	360	2.1
F-Test	**	**	NS	*	NS	*	***	NS
SED	0.10	0.07		0.2		8	9	
LSD$_{0.05}$	0.20	0.1		0.4		15	17	
Linear	***	**		*		NS	***	
Quadratic	NS	NS		NS		NS	NS	
Wheat Line (WL)								
LQ1299A	4.81	12.1	77.0	34.2	77	207	374	2.0
LQ1315A	4.83	12.0	77.7	34.2	78	195	373	2.1
F-Test	NS	***	***	NS	***	***	NS	***
SED		0.04	0.06		0.3	3		0.04
LSD$_{0.05}$		0.07	0.1		0.5	7		0.08
Seeding Rate (SR)								
200 seeds m^{-2}	4.69	12.1	77.1	34.3	77	166	349	2.3
400 seeds m^{-2}	4.95	12.0	77.6	34.0	78	237	398	1.8
F-Test	***	***	***	**	NS	***	***	***
SED	0.04	0.04	0.06	0.1		3	4	0.04
LSD$_{0.05}$	0.08	0.07	0.1	0.2		7	9	0.08
Seeding Depth (SD)								
2.5 cm	4.82	12.1	77.3	34.0	78	208	383	2.1
5.0 cm	4.82	12.0	77.4	34.3	77	195	364	2.1
F-Test	NS	NS	NS	**	NS	***	***	NS
SED				0.1		3	4	
LSD$_{0.05}$				0.2		7	9	
WL × SR	NS	NS	NS	NS	*	NS	NS	**

(***) Significant at $P < 0.001$. (**) Significant at $P < 0.01$. (*) Significant at $P < 0.05$. (NS) Not Significant. (SED) Standard error of the difference. (LSD$_{0.05}$) Least Significant Difference at $P < 0.05$. (Ŧ) Planting date as determined by soil temperature triggers. Planting Date (PD) 1 corresponds to a soil temperature of 0 - 2.5°C, or as soon after this trigger soil temperature as the site could be planted. Each successive PD corresponds to a 2.5°C increase in soil temperature from the previous PD. Only interactions with significant effects have been included.

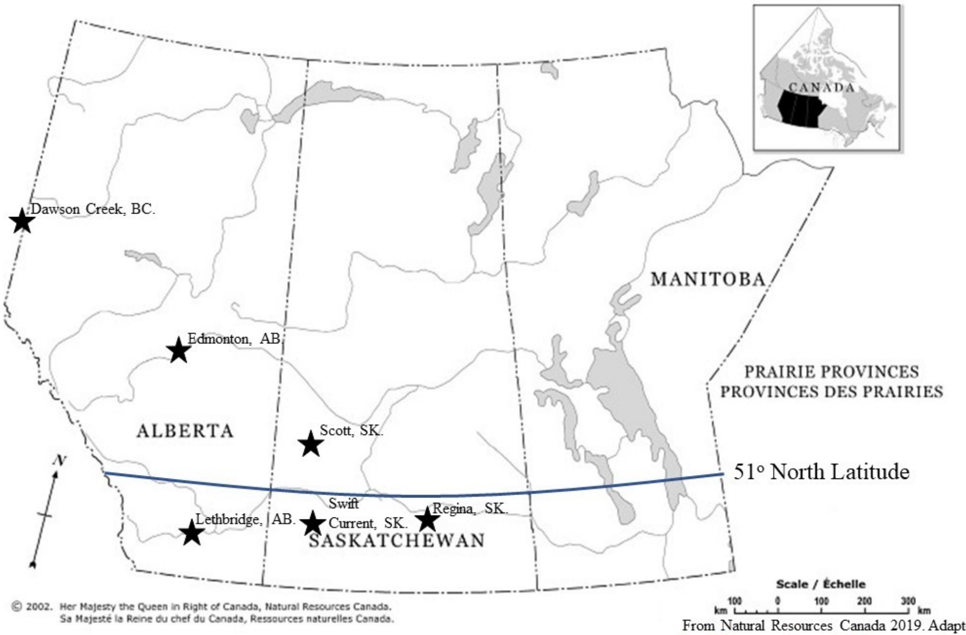
(¥) Data not included from four location × years, Regina, Swift Current, Edmonton 2015, and Lethbridge 2016.

Table 3-4. Least square mean values for crop physiological development stage, duration, and related period lengths for ultra-early planted wheat.

	Days to Emergence	**Days to Anthesis**	**Days to Maturity**	**Emergence to Anthesis (Days)**	**Anthesis to Maturity (Days)**	**Emergence to Maturity (Days)**
Planting Date[Ŧ] (PD)						
1 (Earliest)	25.4	82.8	124.7	58.0	43.3	102.2
2	18.9	76.4	117.7	58.2	42.2	101.4
3	14.5	70.2	110.9	55.5	41.2	98.1
4 (Latest)	11.4	66.1	104.7	55.0	39.0	95.6
F-Test	***	***	***	***	***	***
SED	1.6	1.6	1.6	0.7	0.8	1.1
LSD$_{0.05}$	3.2	3.1	3.1	1.3	1.6	2.3
Linear	***	***	***	***	***	***
Quadratic	NS	NS	NS	NS	NS	NS
Wheat Line (WL)						
LQ1299A	17.3	73.7	114.4	56.6	41.4	99.4
LQ1315A	17.8	74.0	114.6	56.8	41.5	99.2
F-Test	**	*	NS	NS	NS	NS
SED	0.1	0.1				
LSD$_{0.05}$	0.3	0.3				
Seeding Rate (SR)						
200 seeds m^{-2}	18.3	74.0	115.2	56.3	41.9	99.1
400 seeds m^{-2}	16.9	73.7	113.9	57.0	41.0	99.5
F-Test	***	NS	***	**	**	NS
SED	0.1		0.2	0.2	0.2	
LSD$_{0.05}$	0.3		0.4	0.4	0.5	
Seeding Depth (SD)						
2.5 cm	17.0	73.5	114.2	56.8	41.5	99.5
5.0 cm	18.1	74.2	114.8	56.6	41.4	99.1
F-Test	***	***	**	NS	NS	NS
SED	0.1	0.1	0.2			
LSD$_{0.05}$	0.3	0.3	0.4			
PD × SD	**	NS	NS	NS	NS	NS
PD × SR	**	NS	NS	NS	NS	*
WL × SR	NS	*	NS	NS	NS	NS
PD × WL × SR	NS	*	NS	NS	*	NS

(***) Significant at $P < 0.001$. (**) Significant at $P < 0.01$. (*) Significant at $P < 0.05$. (NS) Not Significant. (SED) Standard error of the difference. (LSD$_{0.05}$) Least Significant Difference at $P < 0.05$. (Ŧ) Planting date as determined by soil temperature triggers. Planting Date (PD) 1 corresponds to a soil temperature of 0 - 2.5°C, each successive PD corresponds to a 2.5°C increase in soil temperature from the previous PD. Only interactions with significant effects have been reported. Data not reported for all environments.

3.8 Figures



From Natural Resources Canada 2019. Adapted by G. Collier http://ftp.geogratis.gc.ca/pub/nrcan_rncan/raster/atlas_6_ed/reference/bilingual/prairies_out.jpg

Figure 3-1. Geographical distribution of test locations for the assessment of planting date, rate, depth and wheat line on ultra-early wheat seeding systems on the northern Great Plains. (The Atlas of Canada – Natural Resources Canada). Modified by G. Collier. http://ftp.geogratis.gc.ca/pub/nrcan_rncan/raster/atlas_6_ed/reference/bilingual/prairies_out.jpg).

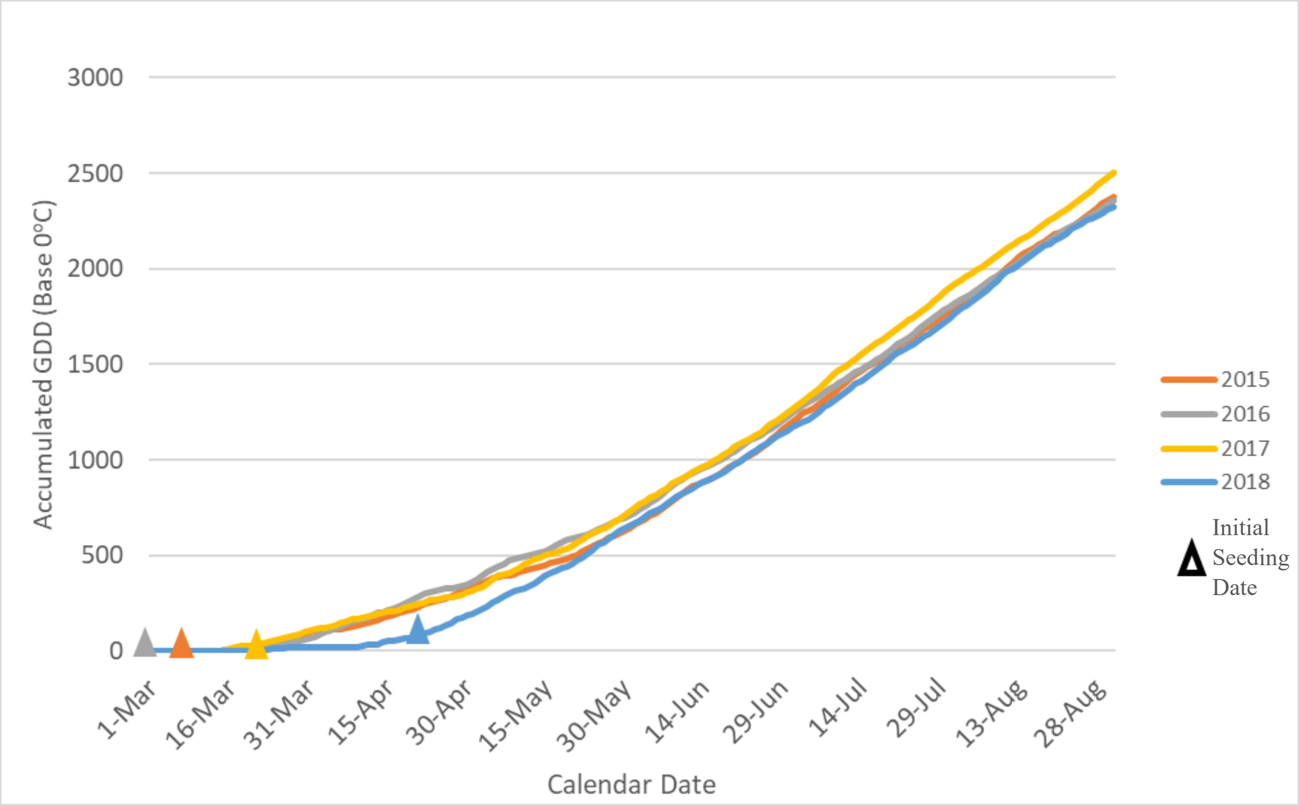


Figure 3-2. Growing degree day (base 0°C) (GDD B_0) accumulation at Lethbridge, Alberta sites 2015 - 2018. The position of each triangle indicates the initial seeding date in each year in relation to GDD B_0 accumulation for the growing season (March 1 to September 1).

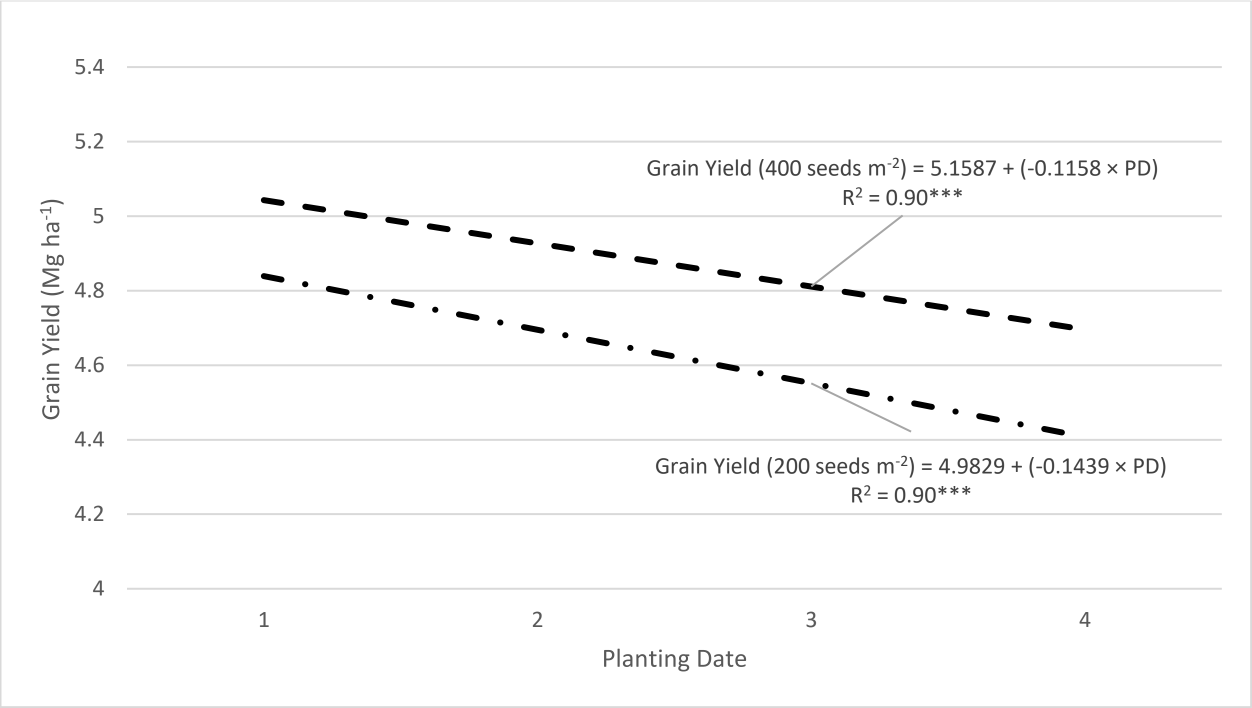


Figure 3-3. Wheat grain yield as a function of planting date (PD) at 13 environments on the northern Great Plains. PD 1 corresponds to a soil temperature of 0 - 2.5°C, with each successive PD equal to a 2.5°C increase in soil temperature. The lines represent linear regressions for grain yield when planted at 200 seeds m^{-2} or 400 seed m^{-2}. (***) Significant at $P < 0.001$.

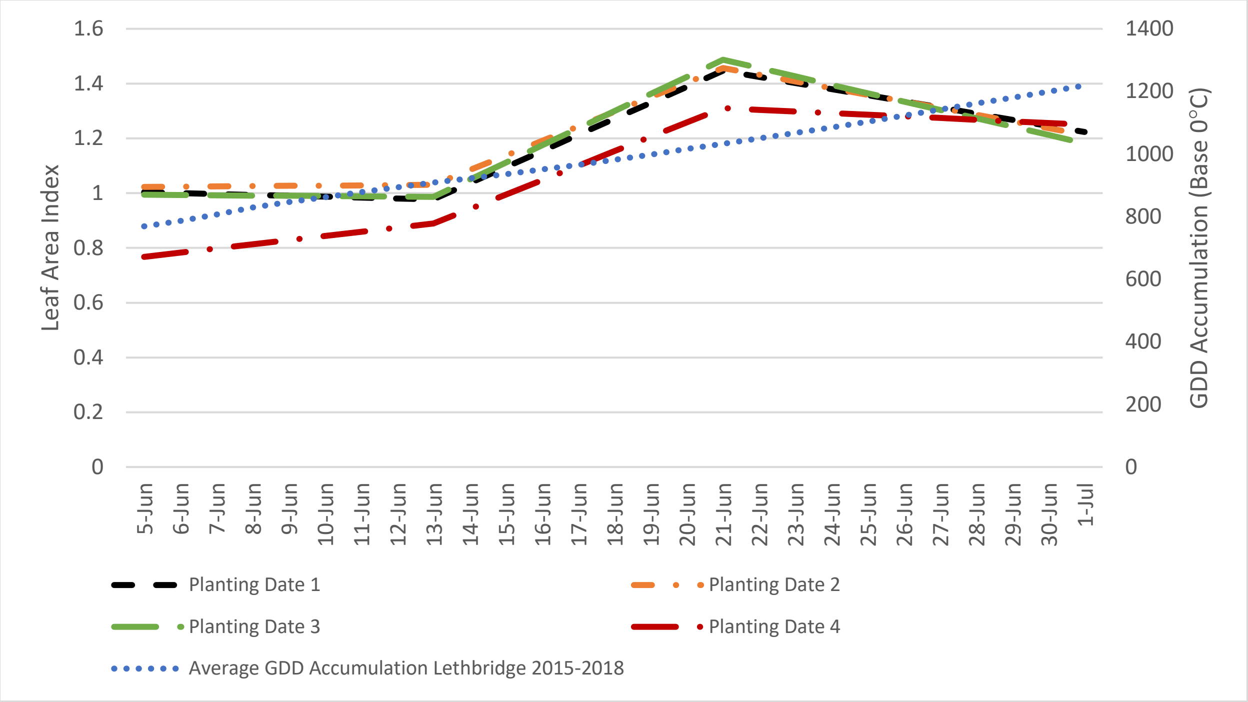


Figure 3-4. Average leaf area index (LAI) values from 5 June to 1 July at Lethbridge, Alberta sites 2015 – 2018 for each planting date, overlaid with 2015 – 2018 average GDD B_0 accumulation during the same time period. Planting dates 1 – 3 had significantly great LAI values than planting date 4 on June 5 ($P < 0.05$). No significant differences in LAI between planting times was present 13 June to 1 July.

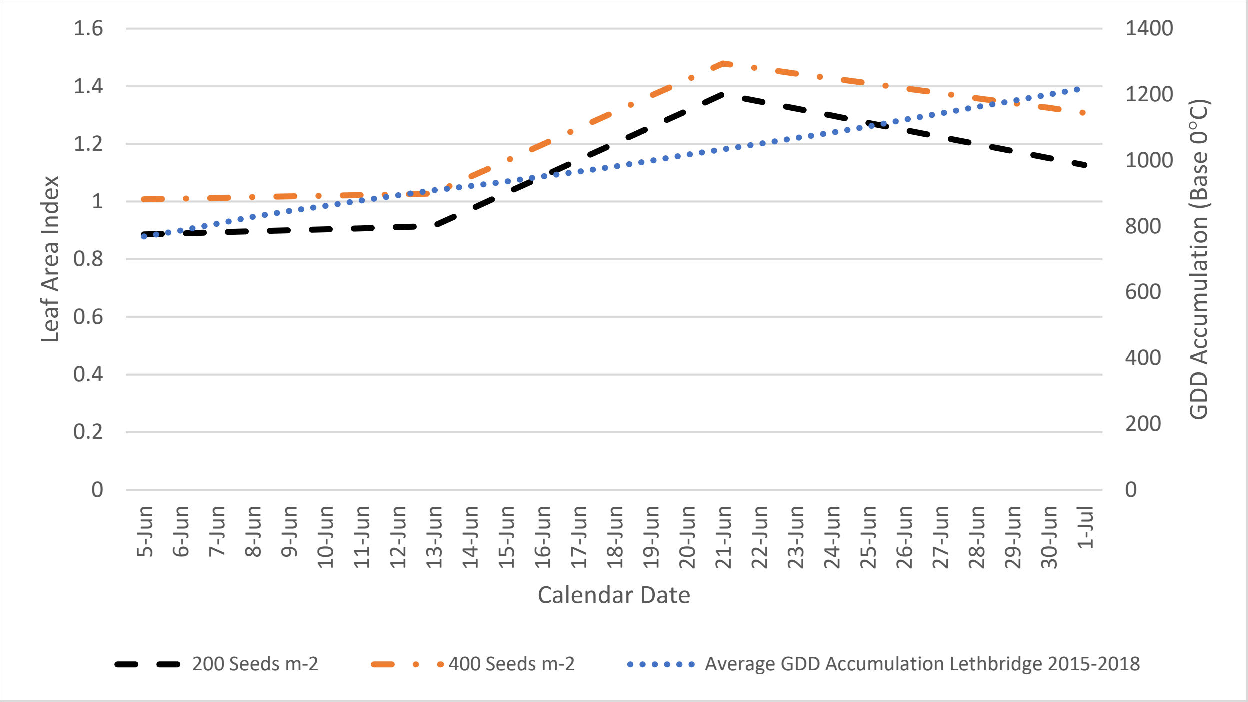


Figure 3-5. Average leaf area index (LAI) values from 5 June to 1 July at Lethbridge, Alberta sites 2015 -2018 for each seeding rate, overlaid with 2015 – 2018 average GDD B_0 accumulation during the same time period. The optimum seeding rate (400 seed m^{-2}) had significantly greater LAI than the 200 seeds m^{-2} seeding rate on 5 June and 13 June ($P < 0.05$). No significant differences in LAI between seeding rates was present 21 June to 1 July.

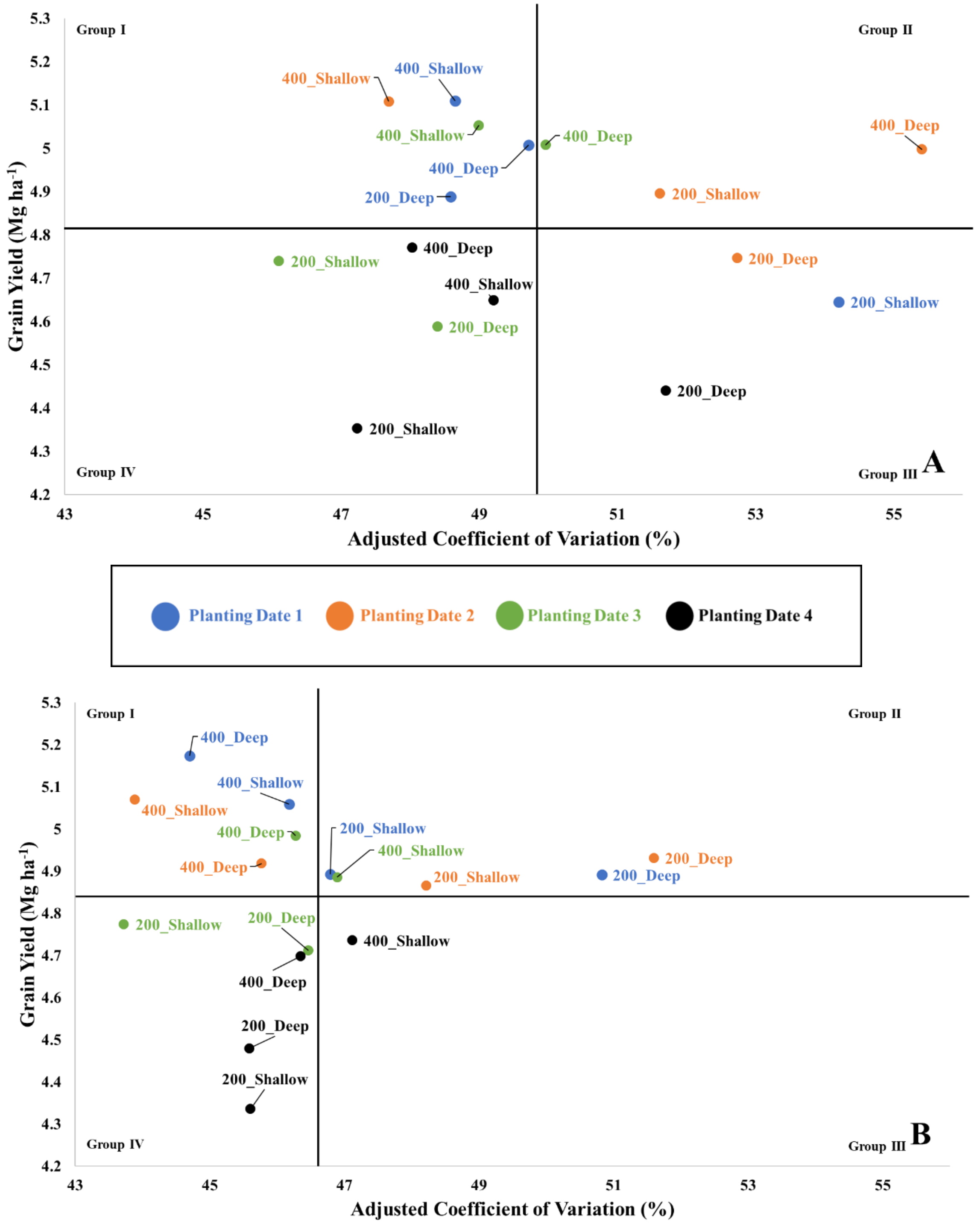


Figure 3-6. Biplots summarizing grain yield means vs. adjusted coefficient of variation (aCV) for each wheat line; LQ1299A (**A**), and LQ1315A (**B**). Abbreviations are as follows: I) The first number represents the seeding rate (400 - 400 seeds m^{-2}, 200 - 200 seeds m^{-2}). II) The second word represents the sowing depth (Shallow – 2.5 cm, Deep – 5 cm). III) Colours represent the planting date as indicated in the legend above (Planting Date 1-4, 1 equaling 0 - 2.5°C soil temperature). Grouping categories are divided by a vertical line representing the mean aCV and a horizontal line representing the mean grain yield: Group I: high mean, low variability; Group II: high mean, high variability; Group III: low mean, high variability; Group IV: low mean, low variability.

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4.0 Canadian spring hexaploid wheat (*Triticum aestivum* L.) cultivars exhibit broad adaptation to ultra-early wheat planting systems[3]

4.1 Introduction

Canada was the sixth largest global producer (32.3 MT) and third largest exporter (22.8 MT) of wheat (*Triticum aestivum* L.) in 2019 (FAOSTAT 2021). The average wheat grain yield in Canada has more than doubled from 1.5 Mg ha^{-1} (1961-1970) to 3.2 Mg ha^{-1} (2010-2019) as a result of improved genetics, agronomic management, synthetic fertilizer use, adoption of new technology and mechanization, and increased growing system efficiency (FAOSTAT 2021, Beres et al. 2020). Ultra-early seeding systems have been proposed as a new management approach to increase current grain yield; and enhance the resiliency of Canadian spring wheat growing systems against impending negative yield impacts of climate change (Collier et al. 2021, Collier et al. 2020). Wheat grain yield reduction on the northern Great Plains has been predicted in multiple studies, primarily as a result of reduced in-season precipitation and increased daily temperatures during the critical grain fill period (Collier et al. 2020, Qian et al. 2019, He et al. 2018, and Kouadio et al. 2015). An early seeding strategy to avoid environmental stress during grain filling periods has been evaluated in the Australian grain belt and the United States Pacific Northwest (Hunt et al. 2018, Kirkegaard et al. 2015). Ultra-early wheat seeding systems for the northern Great Plains growing region are based on the use of soil temperatures to trigger planting, combined with optimized agronomic management, and are characterized by planting into soils at 2°C to 6°C and maintaining optimal seeding rates of 400 seeds m^{-2}. Previously, we evaluated ultra-early wheat seeding systems using experimental cold tolerant spring wheat lines and one Canada Western Red Spring (CWRS) cultivar as a standard check (Collier et al. 2020). Wheat cultivar did not impact grain yield stability in this study; however, a

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[3] *This chapter has been published in:* G. R. S. Collier, D. M. Spaner, R. J. Graf, C. A. Gampe and B. L. Beres. 2022. Short Communication: Canadian spring hexaploid wheat (*Triticum* aestivum L.) cultivars exhibit broad adaptation to ultra-early wheat planting systems. *Canadian Journal of Plant Science* 102: 442-448. doi 10.1139/cjps-2021-0155

broad evaluation of multiple Canadian spring wheat market classes and hexaploid spring wheat cultivars for adaptation to ultra-early spring wheat growing systems has not been completed to date. The purpose of the present study is to investigate grain yield and grain yield stability of multiple western Canadian spring wheat market classes and registered western Canadian hexaploid spring wheat cultivars planted in an ultra-early wheat seeding system on the northern Great Plains.

4.2 Materials and methods

We conducted the present study at three sites in western Canada in 2017 and 2018, and one site in 2019 resulting in seven total site-years (Table 4-1). The experiment was seeded as a factorial randomized complete block design with four blocks. Treatment combinations consisted of two seeding dates and twelve wheat cultivars (Table 4-2). Wheat cultivars were selected based on a combination of the significance of the seeded area of the cultivar within its wheat class in 2016, and the widest genetic variation available within commercial Canadian cultivars for vernalization, photoperiod and height genes (Canadian Grain Commission 2021, Statistics Canada 2021, Kamran et al. 2013). Soil temperatures were determined, and seeding was triggered as previously reported (Collier et al. 2021, 2020). To identify spring wheat lines and classes with increased sensitivity to ultra-early seeding, a sowing density of 200 viable seeds m^{-2}, known to be sub-optimal in ultra-early wheat seeding systems, was used (Collier et al. 2021). Seeding equipment and operations, nutrient and pest management and data collection was completed as reported by Collier et al. (2021).

Statistical analyses were completed using the MIXED procedure of SAS (Version 9.4, Cary, NC, USA) and followed the procedure of Collier et al. (2021), with the exception that the combined ANOVA was completed with site-year, replication, soil temperature trigger and cultivar as variables in the CLASS statement (SAS Institute 2018).

An LSMESTIMATE statement for grain yield with soil temperature trigger × cultivar as a fixed effect was used to compare the grain yield of each cultivar when seeded at either 2°C or 8°C soil temperature.

A biplot grouping methodology using mean grain yield on the vertical axis and adjusted coefficient of variation (aCV) on the horizontal axis, as originally described by Francis and Kannenberg (1978) and modified by Döring and Reckling (2018), was used to explore system stability and variability of grain yield with multiple wheat cultivars and wheat classes. We categorized data on the biplots into four groups/quadrants divided by the mean aCV and the mean grain yield of the growing system: (Group I) high mean grain yield and low variability, (Group II) high mean grain yield and high variability, (Group III) low mean grain yield and high variability, and (Group IV) low mean grain yield and low variability.

4.3 Results

4.3.1 Environmental conditions

Planting was earlier, and all sites experienced more cold stress after seeding in 2017 than in 2018 or 2019. The earliest planting was in Lethbridge, AB on March 20 of 2017. The Scott, SK site was planted on March 31, and the Edmonton, AB site was planted on April 7 of 2017. Prolonged snow cover in 2018 resulted in all locations planting between April 23 and April 27; in 2019, the first planting date at the Lethbridge site was April 2. After initial plantings, each site-year experienced multiple nights of ambient air temperatures below freezing. In 2017, the Scott site experienced the harshest conditions of the study, with 27 nights of ambient air temperatures below freezing after planting; the lowest temperature observed was -9.4°C. The Lethbridge and Edmonton sites recorded 17 and 14 nights, respectively, of ambient air temperatures below freezing after planting in 2017, with temperatures as low as -7.6°C and -6.1°C, respectively. Accumulated precipitation fell below the 30-year average for all seven site-years. The Lethbridge site received the least precipitation in 2017 and 2019, which was 66% and 67% of the 30-year average respectively, and the Scott site received the least precipitation in 2018, (70% of the 30-year average). Initial planting dates, environmental information and additional climatic, and site-specific information is included in Table 4-1.

4.3.2 Grain yield, grain quality, and plant establishment

Planting trigger did not have a significant effect on grain protein content, grain test weight, thousand kernel weight, grain yield or plant establishment. There was no negative impact of ultra-early seeding on grain quality or grain yield (Table 4-2).

Wheat cultivars and classes varied ($P < 0.001$) for all grain yield, grain quality, and plant establishment variables (Table 4-2). In general, the CWRS and Canada Prairie Spring Red (CPSR) cultivars displayed the greatest grain protein concentration and lower grain yield, and the

Canada Western Soft White Spring (CWSWS), Canada Western Special Purpose (CWSP) and cold tolerant (CT) experimental lines accumulated lower grain protein content and greater grain yield. Potential differential performance of a cultivar planted at 2°C soil temperature versus at 8°C soil temperature may have been masked by the lack of a significant planting soil temperature × cultivar interaction. This was further confirmed by performing an LSMEstimate within the PROC MIXED procedure of SAS which did not detect yield differences between the ultra-early 2°C and 8°C soil temperature planting time (Table 4-2). Analysis of plant establishment data indicated no difference within cultivars in the number of live plants between ultra-early and conventional planting timing with the exception of CDC Plentiful (CWRS), which displayed a greater number of viable plants at the ultra-early planting time (data not shown).

4.3.3 Wheat class and grain yield stability

In order to visualize the effect of planting date, wheat cultivar and wheat class on grain yield and growing system stability, a modified biplot grouping methodology was employed. The original methodology of Francis and Kannenberg (1978) was modified to include an adjusted coefficient of variation (aCV) in the place of a traditional coefficient of variation as described by Döring and Reckling (2018). The use of an aCV negates the dependence of system stability on the magnitude of the realized grain yield. Biplot A in Figure 4-1 illustrates the stability of each cultivar when planted ultra-early into 2°C soil and when planted into soil at 8°C. All points related to the 8°C soil temperature planting trigger are located right of the mean aCV value and are located in Groups II and III of the biplot; which are defined by lower grain yield stability than the data points in Groups I and IV. All of the cultivars planted ultra-early are represented on the left side of the mean aCV value, in Groups I and IV. This indicates the greatest grain yield stability occurred when the cultivars in this study were planted at an ultra-early timing triggered by 2°C soil temperatures despite the harsh environmental conditions experienced after planting. Biplot B presents the same data points grouped by Canadian wheat market class rather than by specific cultivar. The CWSWS and CWSP cultivars had the greatest grain yield, while CPSR and CWRS cultivars had relatively lower grain yield. Relative grain yield between wheat classes was consistent regardless of planting time. All wheat classes performed similarly in response to ultra-early planting, with similar grain yields relative to planting at 8°C, but exhibited improved grain yield stability and thus, improved growing system stability when planted in 2°C soil.

4.4 Discussion

We have reported that planting wheat ultra-early based on soil temperature on the northern Great Plains of western Canada not only maintained grain yield, but can also lead to increased grain yield over delayed planting (Collier et al. 2021, 2020). These previous studies reported that specially developed cold tolerant spring wheat lines were not required to successfully plant wheat ultra-early; however, these studies only evaluated one cultivar from the CWRS wheat class. Here, we evaluated nine wheat cultivars from four Canadian wheat market classes, as well as three cold tolerant lines. In all cases, when wheat cultivars were planted earlier (2°C soil temperatures in the top 5 cm of soil) the growing system stability was superior to the same cultivars planted later at 8°C soil temperatures. Collier et al. (2021) evaluated manipulations to agronomic management of ultra-early wheat seeding systems in order to increase grain yield and growing system stability, and reported that using optimal seeding rates (400 seeds m^{-2}) was a critical agronomic management strategy to maintain or increase grain yield and growing system stability in an ultra-early wheat seeding system. In the present study, a sub-optimal seeding rate (200 seeds m^{-2}) was used in order to identify wheat cultivars or classes susceptible to decreases in grain yield or growing system stability as a result of ultra-early seeding. The lack of a negative response in grain yield and growing system stability when planted ultra-early at sub-optimal seeding rates indicates that broad adaptation to ultra-early seeding systems exists within a majority of Canadian wheat germplasm and commercially available cultivars representing dominant market classes in western Canada.

This work corroborates the results of previous studies and supports the expansion of current ultra-early wheat growing system recommendations to include additional wheat classes in western Canada. Spring wheat from Canadian wheat market classes including, but not limited to, CWRS, CWSWS, CPSR, CWSP and Canada Northern Hard Red (CNHR) can successfully be planted in ultra-early wheat growing systems. The impacts of a changing climate including fewer precipitation events and increased daily temperatures may disproportionately affect higher-yielding, lower protein wheat cultivars such as CWSWS and CWSP class cultivars that require longer grain-filling periods and longer growing seasons. Shifting planting to earlier in the season and optimizing agronomic management within an ultra-early wheat growing system acts as an avoidance mechanism to negate, or reduce, future grain yield losses resulting from climate change. In such a scenario, a shift to ultra-early seeding may serve as a mitigation strategy to maintain current grain yield potential and achieve further yield gap closure on the northern Great Plains.

4.5 Conclusions

Canadian hexaploid spring wheat cultivars exhibited broad suitability for use in ultra-early wheat growing systems. The most successful ultra-early wheat growing systems will incorporate commercial Canadian hexaploid spring wheat cultivars, planted at optimal seeding densities of not less than 400 seeds m^{-2}, when soil temperatures of 2°C - 6°C in the top 5cm of the soil surface are first observed. Ultra-early growing systems incorporating these management tactics will lead to increased grain yield and grain yield stability relative to current conventional wheat growing practices and increase the resiliency of wheat growing systems on the northern great plains.

4.6 Acknowledgements

The authors wish to thank many contributing technicians and staff for their time and effort in the completion of this study: at Agriculture and Agri-food Canada Lethbridge, (Ryan Dyck, Steve Simmill, Warren Taylor, and many seasonal staff), at Agriculture and Agri-Food Canada Scott, (Arlen Kapiniak and many seasonal staff), and the staff at the University of Alberta (Klaus Strenzke, Muhammad Iqbal, Fabiana Dias, Joseph Moss, Tom Keady, Katherine Chabot, Lindsay Jessup and Russell Puk). This study was funded by the Alberta Wheat Commission, project number 17AWC44A, and additional core funding was provided by the Western Grains Research Foundation. We thank the Alberta Wheat Commission, Western Grains Research Foundation and the wheat producers of Alberta for their support.

4.7 Tables

Table 4-1. Post-seeding air temperature extremes and cumulative freezing events recorded at each location × year.

Location	Latitude/Longitude	Agroecological Region	Soil Zone, Texture	Soil Organic Matter	pH	Average Yearly Precipitation* (mm)	Year	Actual Precipitation (mm)	Earliest Seeding Date**	Number of days with air temperature below 0°C after initial seeding date	Lowest air temperature recorded after seeding (°C)
Edmonton, Alberta	53°33’N 113°29’W	Parkland	Black, Loam	9.5%	5.9	446	2017	416	April 7	14	-6.1
							2018	391	April 27	1	-1.2
Lethbridge, Alberta	49°41’N 112°50’W	Western Prairies	Dark Brown, Clay Loam	4.6%	8.0	380	2017	249	March 20	17	-7.6
							2018	284	April 23	2	-1.2
							2019	253	April 2	16	-6.9
Scott, Saskatchewan	52°21’N 108°49’W	Western Prairies	Dark Brown, Clay Loam	2.9%	6.0	366	2017	300	March 31	27	-9.4
							2018	257	April 24	5	-3.1

* 1981-2010 average yearly precipitation accumulation. ** Based on 0°C soil temperature trigger date

Table 4-2. Least square means for grain yield, grain quality parameters and plant counts for multiple western Canada wheat cultivars/classes planted ultra-early.

	Protein (%)	Test Weight (kg hL^{-1})	Thousand Kernel Weight (g)	Plant Count (Plants 6m row^{-1})	Grain Yield (Mg ha^{-1})		
Planting Trigger							
2°C Soil Temperature	12.8	80.3	32.8	214	4.01		
8°C Soil Temperature	12.6	80.7	32.4	203	3.79		
F Test	NS	NS	NS	NS	NS		
LSD$_{0.05}$							
Cultivar (Class)					Grain Yield (Mg ha^{-1})	Grain Yield at 2°C Soil Temperature Trigger[Ŧ]	Grain Yield at 8°C Soil Temperature Trigger[Ŧ]
5700PR (CPSR)	14.3	81.6	36.4	206	3.59	3.67	3.51
AC Andrew (CWSWS)	11.3	79.4	33.5	204	4.20	4.37	4.03
Conquer (CPSR[¥])	13.9	80.8	36.6	214	3.79	3.88	3.71
AC Foremost (CPSR[¥])	13.3	80.1	38.0	192	3.61	3.63	3.58
LQ1282A (CT)	10.9	81.1	28.4	200	4.28	4.47	4.09
LQ1299A (CT)	11.8	79.5	30.3	205	3.92	4.07	3.77
LQ1315A (CT)	11.7	80.3	31.1	197	4.00	4.19	3.82
Pasteur (CWSP)	12.2	81.6	33.4	218	4.35	4.50	4.19
CDC Plentiful (CWRS)	14.0	80.4	39.8	228	3.63	3.76	3.51
AC Sadash (CWSWS)	10.8	80.2	33.5	207	4.27	4.40	4.15
CDC Stanley (CWRS)	13.9	79.2	28.6	221	3.52	3.49	3.55
AC Stettler (CWRS)	14.1	81.7	31.8	216	3.61	3.67	3.54
F Test	***	***	***	***	***		
LSD$_{0.05}$	0.5	0.6	0.9	12	0.22		

(***) Significant at $P < 0.001$. (**) Significant at $P < 0.01$. (*) Significant at $P < 0.05$. (NS) Not Significant. (LSD$_{0.05}$) Least Significant Difference at $P < 0.05$.

[Ŧ] There was no difference in grain yield at 2°C and 8°C soil temperature planting triggers for any individual cultivar ($P < 0.05$).

[¥] Moved to the Canada Northern Hard Red (CNHR) class after 2016.

Yield and grain quality parameters do not include data from Lethbridge in 2018 due to plot damage, plant counts include data from all seven locations.

Abbreviations: Canada Prairie Spring Red (CPSR), Canada Western Soft White Spring (CWSWS), cold tolerant (CT), Canada Western Special Purpose (CWSP), Canada Western Red Spring (CWRS).

4.8 Figures

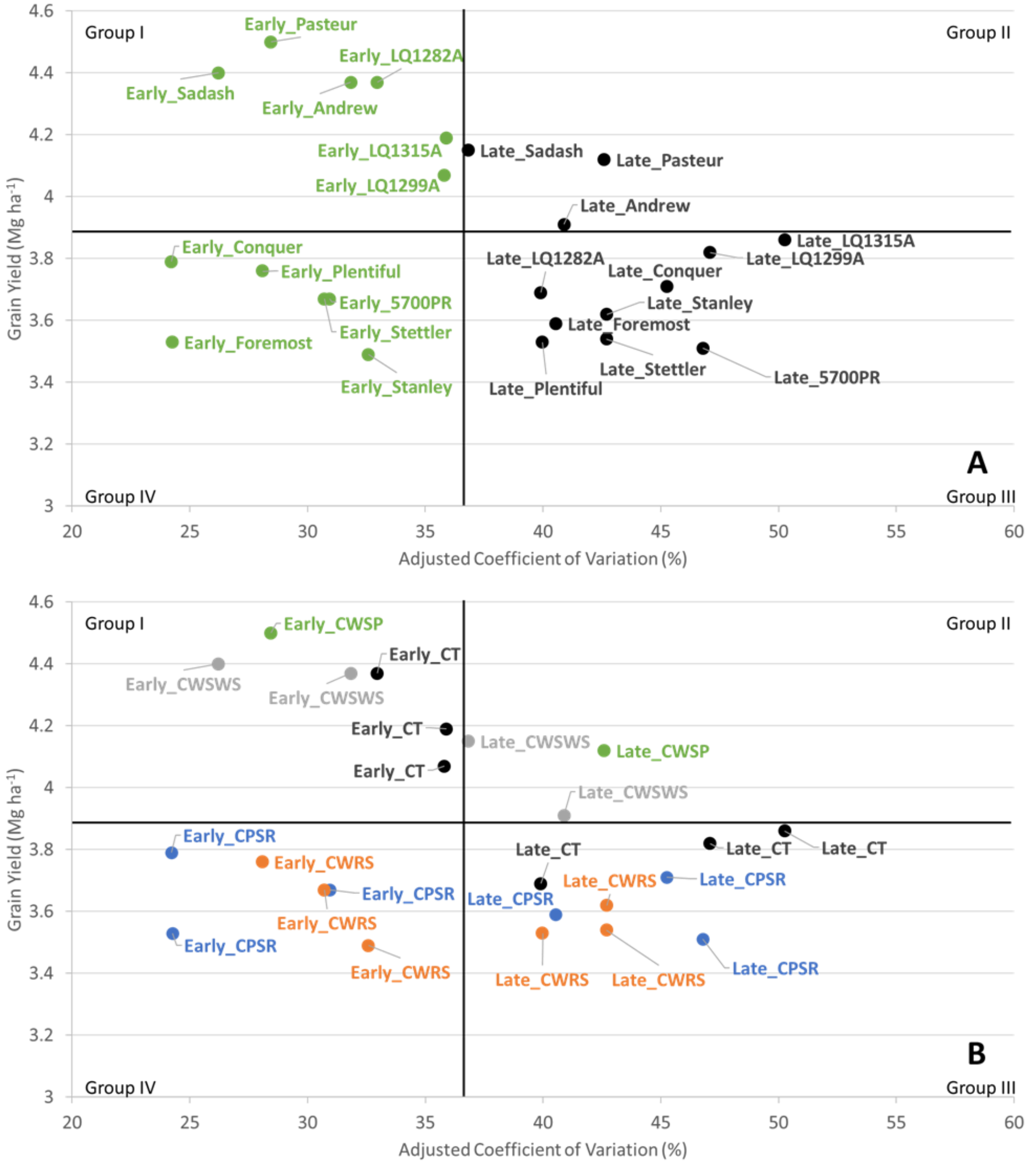

Figure 4-1. Biplots summarizing grain yield means versus adjusted coefficient of variation (aCV) for each wheat cultivar planted at each soil temperature (**A**), and for each Canadian wheat market class planted at each soil temperature (**B**). Abbreviations are as follows: (I) The first word represents the soil temperature at planting (Early - 2°C soil temperature, Late - 8°C soil temperature). (II) The second word denotes the wheat cultivar in Biplot A (See Table 4-2 for full wheat cultivar names), or the functional class of the wheat cultivar in Biplot B (CWRS – Canada Western Red Spring, CPSR – Canada Prairie Spring Red, CWSWS – Canada Western Soft White Spring, CWSP – Canada Western Special Purpose, CT – cold tolerant). The use of colour serves to group data points by soil temperature at planting (Biplot A), and by wheat functional class (Biplot B). Biplot Group definitions: (Group I) high mean grain yield and low variability, (Group II) high mean grain yield and high variability, (Group III) low mean grain yield and high variability, and (Group IV) low mean grain yield and low variability.

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5.0 Fall-applied residual herbicides improve broadleaf weed management in ultra-early wheat (*Triticum aestivum* L.) production systems on the northern Great Plains[4]

5.1 Introduction

Grain production on the northern Great Plains is partially limited by regional environmental conditions primarily characterized by short frost-free growing periods and high average daily temperatures during sensitive wheat (*Triticum aestivum* L.) reproductive growth stages (Lanning et al. 2010, He et al. 2012, Thomas and Graf 2014, Iqbal et al. 2016, Fatima et al. 2020). Wheat grain production in the region has increased by 38% from 1961-1970 to 2008-2017, despite a decrease in planted area of 31% over the same period (Statistics Canada 2021). Hatfield and Beres (2019) reported an average increase in realized on-farm wheat grain yield of 0.6 kg ha^{-1} $year^{-1}$ from 1960 to 2017, however, an average increase in grain yield potential, the maximum attainable grain yield in an unconstrained environment, of 0.9 kg ha^{-1} $year^{-1}$ was reported over the same period. Previous studies in similar wheat growing regions around the world have reported that shifting spring wheat planting earlier in the growing season resulted in greater grain yield and could potentially reduce the gap between realized and potential grain yields (Kirkegaard et al. 2015, Hunt et al. 2018, Beres et al. 2020). Collier et al. (2020) evaluated ultra-early planting of wheat on the northern Great Plains of North America and identified soil temperatures from 2°C to 6°C as indicators of the optimum time for planting spring wheat to achieve the greatest grain yield and grain yield stability on the northern Great Plains. Collier et al. (2021) defined grain yield stability as a measure of the variability in grain yield resulting from a particular treatment level, and growing system stability as the overall grain yield stability resulting from multiple applied agronomic management tactics. Collier et al. (2021) reported that the growing system stability of ultra-early wheat growing systems could be enhanced by combining early planting with optimum seeding rates of not less than 400 viable seeds m^{-2}.

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[4] *This chapter has been published in:* G. R. S. Collier, D. M. Spaner, L.M. Hall, R. J. Graf, and B. L. Beres. 2022. Fall-applied residual herbicides improve broadleaf weed management in ultra-early wheat (*Triticum aestivum* L.) production systems on the northern Great Plains. *Canadian Journal of Plant Science*. 102: 1115-1129. doi 10.1139/CJPS-2022-0036

Wheat planted at traditional timings later in the growing season relies on pre-seeding weed control, followed by in-crop herbicide applications to manage weed competition. Ultra-early wheat planting systems as described by Collier et al. (2020, 2021, 2022) necessitate planting prior to the emergence of most weeds, while soil temperatures are cold (prior to 6°C). Early crop emergence resulting from ultra-early planting increases the competitiveness of the crop with weeds that emerge later in the growing season, however, also negates the use of a foliar pre-emergent or pre-plant herbicide (Clements et al. 1929, Harker and O'Donovan 2013). Fall-applied soil residual herbicides are used successfully in other crops in western Canada to control early-emerging weeds and maintain low weed pressure during critical weed free periods (Jha and Kumar 2017, Johnson et al. 2018). Weed control benefits of mechanical planting operations may be negated by ultra-early planting systems due to the absence of emerged weeds at planting. Subsequently, ultra-early planting may stimulate weed emergence via early spring soil disturbance (Geddes and Gulden 2017).

Flumioxazin and pyroxasulfone can be applied in the fall or spring prior to planting spring wheat to supplement or replace pre-seeding herbicide applications (Anonymous 2020). For effective activity, pyroxasulfone and flumioxazin require moisture after application to transition the active ingredients from the surface of the soil into soil water solution where they become available for plant uptake (Westra et al. 2015, Eason et al. 2021). Both flumioxazin and pyroxasulfone have low leaching potential and are primarily degraded in the soil by microbial activity which is temperature and moisture dependent (Shaner 2014, Nash 2016). These herbicides effectively form a layer of active ingredient in the soil that weed species must germinate in, infiltrate with roots, or grow through in order to emerge (Westra et al. 2015, Eason et al. 2021). When combined, the two separate modes of action of flumioxazin and pyroxasulfone can act sequentially on the same weed species, reducing selection for resistance (Beckie 2006, Beckie and Reboud 2009, Beckie and Harker 2017). On the northern Great Plains fall application of these active ingredients promotes movement of the herbicides into soil water solution when snow cover ablation occurs in the spring. Weed control with fall applications can be more consistent than with spring applications, which are dependent on precipitation after application. Fall applications of these herbicides on the northern Great Plains made after soil temperatures, and subsequently microbial activity, have decreased, do not result in significant degradation of active ingredient in the soil prior to weed emergence the following spring (Cessna et al. 2017, Anonymous 2020).

This study evaluated grain yield, growing system stability, spring wheat tolerance and weed control when flumioxazin and pyroxasulfone were applied to soil alone, and in combination, at multiple rates in the fall prior to ultra-early spring wheat planting the following spring.

5.2 Materials and methods

5.2.1 Site description, experimental design, determination of planting time using soil temperature triggers, and herbicide treatments

This study was conducted at three sites in western Canada in each of 2017 and 2018 and one site in 2019 for a total of seven environments (Table 5-1). Additional information regarding location, soil characteristics, and precipitation at each site is included in Table 5-1. The treatment structure of the experiment consisted of 18 total treatments arranged in a factorial randomized complete block design with four blocks. The treatment combinations consisted of two planting dates and nine herbicide treatments (Table 5-2). Each plot was two meters wide and six meters long, one meter of untreated area was retained between each plot to negate any risk of treatment overlap and maintain an untreated area between each plot to allow verification of weed population uniformity. Herbicide applications were made to the full width of each two-meter plot and extended 50 cm before and after each plot to ensure even soil application through the entire plot area.

The herbicide treatments which included an untreated check and a weed-free check treatment were applied at each trial location the fall before ultra-early spring planting occurred. Applications of flumioxazin, pyroxasulfone, and flumioxazin + pyroxasulfone were made in the after soil temperatures had dropped below 10°C, generally after October 15, and all applications were made prior to the ground freezing. Applications were completed using a motorized sprayer calibrated to deliver a carrier volume of 100 L ha^{-1} at 275 kPa. Flumioxazin and pyroxasulfone were each applied at two rates according to the Health Canada Pest Management Regulatory Agency (PMRA) approved labels for flumioxazin (Valtera™ Herbicide) and pyroxasulfone (Pyroxasulfone 85 WG Herbicide) (Table 5-2). A combination of flumioxazin and pyroxasulfone (flumioxazin + pyroxasulfone) was also applied at two rates as per the PMRA approved label

(Fierce™ Herbicide) (Table 5-2). One herbicide treatment consisted of the lower application rate of flumioxazin + pyroxasulfone in the fall, followed by a post emergent foliar herbicide treatment applied during the following growing season (Table 5-2). Additional information regarding herbicide formulations, active ingredient manufacturers and rate structures is included in Table 5-2.

The following spring, soil temperatures were determined using an Omega™ TPD42 soil temperature probe (Omega Environmental, St-Eustache, QC, Canada) at a 5 cm depth at 10:00 AM each day leading up to planting. The initial planting date was triggered when soil temperatures first reached 2°C and the second planting date was triggered when soils first reached 8°C. In order to more readily identify any effect of soil-applied residual herbicide activity on spring wheat survival, phytotoxicity and grain yield, the wheat line "LQ1299A", as described in Collier et al. (2020, 2021), was planted at a sub-optimal sowing density of 200 viable seeds m^{-2}. Previous studies completed by Collier et al. (2021) indicated optimal seeding rates increased ultra-early wheat growing system stability and thus, if used in this study, could have served to mask potential negative effects of herbicide applications combined with sub-optimal growing conditions.

The post emergent foliar herbicide application required in treatment nine was applied between wheat development stages 12-22 on the Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie (BBCH) crop development scale. The same post emergent foliar herbicide was used at each location: Enforcer® M Herbicide consisting of 80 g acid equivalent L^{-1} fluroxypyr, 200 g active ingredient L^{-1} bromoxynil, and 200 g acid equivalent L^{-1} MCPA ester (Nufarm Agriculture Inc., Calgary, AB, Canada) was applied at 1.25 L ha^{-1} (Table 5-2). Applications of the post emergent treatment were completed using a motorized sprayer calibrated to deliver a carrier volume of 45 L ha^{-1} at 275 kPa.

5.2.2 Planting operations, and nutrient management

Planting equipment varied between locations, but remained similar to the low-disturbance drill built at Agriculture and Agri-Food Canada Lethbridge, which utilizes eight ConservaPak™ knife openers (Model CP129, Vale Industries, Indian Head, SK, Canada) spaced 24 cm apart, and each followed by independent spring-tensioned rubberized packer wheels, Morris™ seed cups (Morris

Industries Ltd., Saskatoon, SK, Canada), a hydraulic seed calibration and product control system from Raven™ (Raven Industries Inc., Sioux Falls, SD, USA), and an air product delivery system from Valmar™ (Valmar Air Inc., Elie, MB, Canada). Low-disturbance seeding systems are required for planting after soil-applied fall applications of flumioxazin and pyroxasulfone. Planting systems that result in movement of soil out of the seed row at planting can remove the soil containing the herbicide layer, thus creating an area in the seed row where no herbicide is present. The drills used in this study planted each plot with a single pass, eight rows wide and resulted in less than 30% soil disturbance, defined by a seed bed utilization value of 30% or less. Seed bed utilization was calculated as follows: seed row opener width, divided by seed row width, multiplied by 100%.

Macronutrient fertilizer (N, P, K, S) was applied based on 0 cm – 15 cm and 15 cm – 60 cm soil test results and recommendations based on grain yield targets appropriate for each location, these soil tests were also used to determine soil organic matter and soil pH at each site (Western Ag Labs PRS® soil test system, Saskatoon, SK, Canada). When required, nutrients were applied as urea nitrogen (46-0-0-0), monoammonium phosphate (11-52-0-0) (Koch Fertilizer, LLC. Wichita, KS, USA), potassium chloride (0-0-60) (The Mosaic Company, Tampa FL, USA), and ammonium sulphate (21-0-0-24) (Yara Canada, Regina, SK, Canada). Fertilizer granules were incorporated as a band below and to the side of the seed row at planting. Wheat seed was treated with a fungicide seed treatment (Raxil PRO - tebuconazole 3.0 g active ingredient L^{-1} + prothioconazole 15.4 g active ingredient L^{-1} + metalaxyl 6.2 g active ingredient L^{-1} [Bayer CropScience Canada Inc., Calgary, AB, Canada]) in order to control seed and soil-borne diseases.

5.2.3 Data collection

Similar to Collier et al. (2021), days to emergence was recorded when an estimated 50% of seedlings had emerged in a plot based on daily visual assessments. Crop anthesis was determined as days from planting date when an estimated 50% of the heads in a plot first extruded anthers based on daily visual assessment. Maturity was defined as physiological maturity and recorded as the days from planting to kernel moisture content in the lower third of the heads being below 40%. The period of time between emergence and maturity was broken into three sub-segments, all reported in days: emergence to anthesis, anthesis to maturity, and emergence to maturity. This is necessary to investigate differential lengths of growth periods between planting dates and herbicide treatments and remove the confounding effect of increased days to emergence often observed with ultra-early planting dates (Collier et al. 2020, 2021).

Plant counts were completed between BBCH 20 to BBCH 49. Two one-meter-long areas of the second and third rows, and second and third last rows of each plot were counted and used to calculate the number of viable plants per 6 m row. Phytotoxicity of herbicide treatments was evaluated visually 14 and 21 days after each plot reached 50% emergence. Visual ratings for general phytotoxicity were assigned to each plot, taking into account any chlorosis, plant height reduction, reduced vigor or biomass reduction. Phytotoxicity ratings were completed on a scale of 0% to 100% with 0% meaning no visual symptoms, and 100% meaning complete plant death. Broadleaf weed control was evaluated at 21, 35, 49, and 63 days after initial crop emergence for each plot using a similar 0% to 100% scale, where 0% was no visual effect on weed control and 100% indicated no broadleaf weeds present in the plot. Visual broadleaf weed control was considered as a combination of absence of individuals versus the untreated check and versus the untreated space between each plot, decreases in biomass resulting from stunted growth, and presence of chlorotic and or necrotic tissue. All visual ratings were completed based on the Canadian Weed Science Society visual rating scales for herbicide efficacy and phytotoxicity (CWSS 2018).

A one-time plant development stage assessment was completed using the Haun wheat development scale after plots had reached a minimum development stage of 4.+ (fifth leaf extending) (Haun 1973). Twenty plants from each plot, regardless of planting date, were evaluated and the average Haun scale stage was reported for each plot on the same day to determine absolute differences in plant development stage between herbicide and planting date treatments. Lodging was assessed on a 1-9 scale with 1 indicating an upright, erect canopy structure and 9 indicating complete lodging (data not shown).

Each plot was harvested in its entirety with a Wintersteiger Nurserymaster Elite plot combine (Wintersteiger AG, Salt Lake City, UT, USA) or a similar combine, all equipped with a straight cut header, crop lifters and pickup reel. Grain samples from each whole plot were weighed after they were dried and corrected to 14% grain moisture content, then used to calculate total grain yield ha^{-1} (Mg ha^{-1}). A two kg subsample from each plot was retained to complete assessments of grain bulk density (kg hL^{-1}), and seed mass (from 500 seeds). Grain protein content was determined using near infrared reflectance spectroscopy for each subsample (Foss Decater GrainSpec, Foss Food Technology Inc., Eden Prairie, MN, USA) (Irvine et al. 2013).

5.2.4 Statistical analyses

The UNIVARIATE procedure in SAS (Version 9.4, Cary, NC, USA) was used to test data for normality and identify outlier observations resulting from any measurement or recording error. These observations were removed prior to completing combined analyses across sites. A mixed model analysis of variance (ANOVA) was used to perform a combined analysis of all environments (location × year combinations) using the MIXED procedure in SAS (Littell et al., 2006, SAS Institute, 2018). Environment, replication within environment and additional interactions with environment were considered random effects while treatment effects (soil temperature at planting, and herbicide treatment) and interactions were considered fixed and significant if $P \leq 0.05$ (Steel et al. 1997). Treatment means were generated using the LSMEANS statement in SAS to generate marginal means of the fixed effects (SAS Institute, 2018).

Error variances between environments were found to be heterogeneous using Akaike's Information Criterion (AICc). Variance heterogeneity was modeled for all analyses by using the RANDOM statement in the MIXED procedure with the GROUP option set to environment which allowed variation in covariance parameters by environment (SAS Institute, 2018). The Satterthwaite approximation was used for degrees of freedom. Environments were then grouped and analyzed based on latitude, with sites north of 51°N latitude (four environments) and south of 51°N latitude (3 environments) being analyzed together due to environmental similarities including the rate of spring snow cover ablation, and the rate of soil temperature increase. These two factors influenced the date of first planting in each environment and the length of time between planting dates at each environment (Table 5-1). A similar grouping was used in the study completed by Collier et al. (2020).

A biplot grouping methodology originally developed by Francis and Kannenberg (1978) was modified and used to evaluate grain yield and growing system stability as well as weed control consistency. The methodology developed by Döring and Reckling (2018) was used to generate an adjusted coefficient of variation (aCV) which was substituted for the traditional coefficient of variation (CV) used by Francis and Kannenberg (1978). The use of an aCV rather than a CV accounts for data conforming to Taylor's Power Law where the value of the CV is dependent upon the yield or weed control and will tend to decrease relative to increases in yield or weed control (Taylor, 1961, Döring et al. 2015). The mean and standard deviation for each treatment combination was estimated using the GLM procedure in SAS and then used to calculate the CV for each treatment combination. The aCV for each treatment combination was then calculated based on the procedure of Döring and Reckling (2018). The aCV was then plotted on the horizontal biplot axis, and the treatment mean on the vertical biplot axis. The average aCV and mean for the treatment combinations were used to group the data into four quadrants: (Group I) high mean grain yield or weed control and low variability, (Group II) high mean grain yield or weed control and high variability, (Group III) low mean grain yield or weed control and high variability, and (Group IV) low mean grain yield or weed control and low variability. In this manner biplots can be used to visualize growing system stability and weed control consistency with either grain yield or weed control plotted on the vertical axis and the aCV plotted on the horizontal axis.

5.3 Results

5.3.1 Environmental conditions

Cold temperatures and freezing events after planting (ambient air temperature less than 0°C) were most extreme for all locations in the 2017 planting season relative to the 2018 and 2019 planting seasons. The earliest soil temperature triggered planting at each location occurred in 2017. Respective initial planting dates were March 20, March 31, and April 7 for Lethbridge, AB, Scott, SK, and Edmonton, AB (Table 5-1). The spring of 2018 had prolonged cold conditions resulting in late snow cover ablation at all sites; as a result, the first planting date at all sites fell between April 23 and April 27. In 2019 the initial planting date at the Lethbridge, AB site was April 2.

Each site recorded ambient air temperatures below 0°C after planting. The Scott, SK site in 2017 recorded the most nights with temperatures below freezing after planting, and the lowest temperature recorded after planting, with 27 nights where the ambient air temperature dropped below freezing and one night where temperatures reached -9.4°C (Table 5-1). In 2017 the Lethbridge, AB site recorded 17 nights where the ambient air temperature dropped below freezing after planting, the most severe being -7.6°C, and the Edmonton, AB site recorded 14 nights with ambient air temperatures below freezing, the most severe of which was -6.1°C (Table 5-1).

In 2018, planting began later than in 2017 at all sites. Later than normal disappearance of snow cover meant frozen soils experienced longer day length and greater light intensity, thus warming quickly and uniformly across sites in western Canada. Initial planting occurred on April 23, 24 and 27 at Lethbridge, AB, Scott, SK, and Edmonton, AB, respectively, and each site recorded relatively few days with ambient air temperatures dropping below zero after planting. The lowest air temperatures reached after the initial planting was -1.2°C at the Edmonton, AB and Lethbridge, AB sites, and -3.1°C at the Scott, SK site. In 2019 in Lethbridge, AB the first planting was completed on April 2, and 16 subsequent nights had ambient air temperatures drop below freezing after the initial planting, the lowest being -6.9°C (Table 5-1).

All seven environments received less precipitation than their 30-year averages. In 2017 and 2019, the Lethbridge, AB site had the greatest precipitation deficit, receiving 66% and 67% of the sites' 30-year average level of precipitation, respectively. In the 2018, growing season the Scott, SK site was most affected by below average precipitation, receiving 70% of the sites' 30-year average precipitation (Table 5-1).

5.3.2 Crop establishment and development

Wheat planted at ultra-early planting dates emerged slower than wheat planted at later, more traditional planting dates. Wheat required an additional 10.3 and 8.0 days to emerge when planted ultra-early at sites north and south of 51°N latitude, respectively (Table 5-3). Despite slower emergence ultra-early planted wheat always emerged, reached anthesis and matured earlier than the later planted treatments (Data not shown). At sites north of 51°N latitude the duration of the emergence to anthesis, anthesis to maturity, and emergence to maturity periods was greater for the ultra-early planting date than the later planting date. At sites south of 51°N latitude only the emergence to anthesis period was significantly longer for the ultra-early planting date than the later planting date (Table 5-3). None of the herbicide treatments had an effect on the length of the growth periods of wheat in this study regardless of geographic location. There was a significant interaction between herbicide and planting date for the anthesis to maturity period at sites south of 51°N latitude; all treatments (except pyroxasulfone at 125 gai ha^{-1} and 150 gai ha^{-1}) required numerically fewer days to progress from anthesis to maturity at the ultra-early planting date. Pyroxasulfone 125 gai ha^{-1} and 150 gai ha^{-1} treatments required a numerically longer time to progress from anthesis to maturity when planted ultra-early. This longer grain-fill period did not lead to increased grain production.

Plant establishment and survival was not affected by herbicide treatment at any location (Table 5-3). Planting date had no effect on wheat populations at sites north of 51°N latitude (Table 5-3). At sites located south of 51°N latitude, ultra-early planting resulted in greater wheat establishment and survival than the later planting time (Table 5-3). There was no negative effect on plant survivability of planting at ultra-early timings.

Relative development stages between planting dates and herbicide treatments were evaluated using a single Haun stage evaluation. No herbicide treatment at any location resulted in a difference in Haun scale rating relative to the untreated check or weed free check, indicating no delays in development as a result of herbicide treatment (Table 5-4, Table 5-5). At the sites north of 51°N latitude there was a difference in plant stage at the time of evaluation with the early planting averaging a Haun stage of 6.4 and the later planting averaging 5.4 (Table 5-4). At the sites south of 51°N latitude the two planting dates no longer exhibited a differential in plant stages at the time of evaluation.

5.3.3 Spring wheat herbicide tolerance and weed control

Herbicide applications did not result in negative effects on plant density, visible phytotoxicity, or delayed growth (Table 5-3, Table 5-4, Table 5-5). No variation in phytotoxicity from the untreated check or weed free check was present with any herbicide treatment, and overall phytotoxicity was negligible with values between 1% to 2% at 14 days after wheat emergence, and between 0% and 2% at 21 days after wheat emergence (Table 5-4, Table 5-5).

Broadleaf weed control was evaluated at four timings: 21, 35, 49, and 63 days after the crop emerged. At sites south of 51°N latitude, planting date did not affect weed control, while at sites north of 51°N latitude greater weed control was observed with the late planting time for the final three weed control evaluations (Table 5-4, Table 5-5). All herbicide treatments provided a weed control benefit over the untreated check at all environments and evaluation timings. Weed control was generally greatest at the earliest evaluation timing, and lowest at the latest evaluation timing. The exception to this was the flumioxazin + pyroxasulfone 160 gai ha^{-1} + in-crop herbicide application treatment at sites north of 51°N latitude where weed control was greater at the later evaluations in response to the post emergent herbicide application (Table 5-4). Overall herbicide efficacy was lower and more variable at sites north of 51°N latitude than sites south of 51°N latitude (Table 5-4, Table 5-5, Figure 5-1a, Figure 5-1b). Individual herbicide treatment effectiveness varied between sites north and south of 51°N latitude as well. Greater separation between individual herbicide treatments based mainly on active ingredient load occurred at sites north of 51°N latitude while performance between treatments remained more similar at sites south of 51°N latitude (Table 5-4, Table 5-5). In general, treatments with either flumioxazin alone or pyroxasulfone alone performed similar to one another. Flumioxazin + pyroxasulfone and flumioxazin + pyroxasulfone with a post emergent herbicide application tended to be the highest performing treatments for broadleaf weed efficacy (Table 5-4, Table 5-5).

The most consistent weed control 63 days after emergence occurred in the sites north of 51°N latitude when flumioxazin 105gai ha^{-1}, flumioxazin + pyroxasulfone 160 gai ha^{-1}, flumioxazin + pyroxasulfone 240 gai ha^{-1}, or flumioxazin + pyroxasulfone 160 gai ha^{-1} + in-crop application treatments were applied. Weed control in the later planted plots tended to be more consistent than the early planted treatments (Figure 5-1a, Figure 5-1c). In sites located south of 51°N latitude the most consistent weed control at 63 days after emergence occurred when flumioxazin 105gai ha^{-1}, pyroxasulfone 150 gai ha^{-1}, flumioxazin + pyroxasulfone 160 gai ha^{-1}, flumioxazin + pyroxasulfone 240 gai ha^{-1}, or flumioxazin + pyroxasulfone 160 gai ha^{-1} + in-crop application was applied (Figure 5-1b, Figure 5-1d). In the sites south of 51°N latitude there was a trend toward more consistent weed control when herbicides were combined with ultra-early planting.

5.3.4 Grain yield and grain quality

Ultra-early planting had no effect on grain protein content regardless of location. Grain yield was significantly higher when wheat was planted at the initial 2°C soil temperature trigger at sites south of 51°N latitude; grain yield at sites north of 51°N latitude did not change as a result of soil temperature triggered planting date. Grain test weight (bulk density) and grain kernel weight were greater at sites south of 51°N latitude when wheat was planted earlier, and greater at sites north of 51°N latitude when planted at the later soil temperature trigger (Table 5-6).

Herbicide treatment had no effect on grain yield, grain protein concentration, or kernel weight at sites south of 51°N latitude (Table 5-6). Grain test weight was affected by the combination of fall-applied flumioxazin + pyroxasulfone with a post emergent application of herbicide, leading to an increase in test weight over the weed free check, while both rates of flumioxazin + pyroxasulfone, as well as the higher application rate of pyroxasulfone resulted in a decrease in grain test weight (Table 5-6). A significant interaction was present between planting trigger and herbicide treatment at sites south of 51°N latitude; this was a result of a greater decrease in grain test weight at later planting times relative to early planting when the active ingredient pyroxasulfone was present in the herbicide treatment (Table 5-6).

At sites north of 51°N latitude, herbicide treatment did not affect grain protein concentration or grain test weight. Grain yield for all herbicide treatments was equal to the grain yield of the weed free check, and multiple herbicide treatments resulted in a greater grain yield than the untreated check. The weed free check produced more grain than the untreated check (Table 5-6). Grain thousand kernel weight was also greater for the weed free check than the untreated check. There were no herbicide treatments which resulted in a grain kernel weight reduction relative to the untreated check; several herbicide treatments resulted in increased grain kernel weight similar to the weed free check (Table 5-6).

In sites north of 51°N latitude, where planting date did not significantly affect grain yield, the biplot representing grain yield stability of the growing system shows few trends regarding planting date (Figure 5-2a). However, the biplot clearly illustrates that lowest grain yield occurred in the untreated check for both planting dates. For sites south of 51°N latitude where grain yield was significantly higher when ultra-early seeding occurred, the biplot for grain yield stability clearly illustrates ultra-early planting increased yield and growing system stability. Furthermore, the use of fall-applied residual herbicides combined with ultra-early planting tended to increase growing system stability of ultra-early planted treatments (Figure 5-2b).

5.4 Discussion

5.4.1 Ultra-early wheat growing system

Spring wheat planted ultra-early at sites located south of 51°N latitude in this study exhibited increases in grain yield and a marked increase in growing system stability. Ultra-early planting at sites south of 51°N latitude resulted in a grain yield increase of 0.45 Mg ha^{-1}, an 18% increase relative to delaying planting until soil reached 8°C. Using an average wheat grain value of \$261.00 Mg^{-1} (September 2015 to December 2021 average southern Alberta price for CWRS wheat, 13.5% protein content), a grower would expect a gross economic benefit of \$117.45 ha^{-1} by shifting to an ultra-early planting date (Alberta Wheat Commission 2021). Greater grain yield at sites south of 51°N latitude resulting from ultra-early seeding can be attributed to increased plant populations, earlier access to spring soil moisture, drought and heat stress avoidance and a longer vegetative growth period similar to the reports of Kirkegaard et al. (2015), Hunt et al. (2018), and Collier et al. (2021).

At sites north of 51°N latitude there was no grain yield difference between ultra-early and later planted wheat and little differential in growing system stability. This result varies from similar studies conducted by Collier et al. (2020), who reported similar yields between ultra-early and later planting dates, but an increase in growing system stability when planting occurred ultra-early. Collier et al. (2021) reported that using optimal wheat seeding rates of 400 viable seeds m^{-2} or more increased growing system stability of ultra-early wheat growing systems. The incongruity between studies at sites north of 51°N latitude may be attributed to the sub-optimal seeding rate of 200 viable seeds m^{-2} used in this study versus the seeding rate of 400 viable seeds m^{-2} used in the study completed by Collier et al. (2020).

5.4.2 Spring wheat tolerance to fall-applied soil residual herbicides

Selectivity in wheat for pyroxasulfone and flumioxazin is dependent upon the ability of wheat to quickly metabolize and detoxify the herbicidally active form(s) of each active ingredient (Niekamp et al. 1999, Tanetani et al. 2013). Due to primary reliance on plant metabolism to complete detoxification, crop safety could be influenced by environmental conditions that reduce plant metabolism. Cold temperatures and saturated soils, both conditions that are commonly encountered by wheat planted ultra-early, can limit the ability of plants to metabolize herbicides (Niekamp et al. 1999, Tanetani et al. 2013, Jha and Kumar 2017). Additionally, we have reported that wheat planted ultra-early takes longer to emerge than later planted wheat, meaning imbibition and initial growth stages are occurring over a longer period of time and are occurring in soil treated with residual herbicides (Collier et al. 2020, 2021). In this respect ultra-early wheat planting systems potentially carry a greater risk of herbicide damage from soil-applied residual herbicides than traditional wheat growing systems. In our study, however, soil-applied residual herbicide treatments did not impact wheat emergence, plant density, or alter phenology in any environment. The absence of crop response to fall-applied residual herbicide use, and the lack of any trends of increasing injury with increased herbicide dose, indicate the crop selectivity of pyroxasulfone and flumioxazin is broad enough to support the safe use of these herbicides in the fall prior to ultra-early planting of wheat the following spring.

5.4.3 Herbicide efficacy and consistency

Extended residual weed control varied between sites located north of 51°N latitude and sites south of 51°N latitude. Overall weed control was greater at the sites south of 51°N latitude. At the sites north of 51°N latitude, at later planting dates early weed escapes were partially controlled by the planting operation which resulted in improved weed control. Variation in soil organic matter, soil moisture and soil pH values influence the level of adsorption of herbicide to soil colloids, and as such, more active ingredient would be expected to be in soil water solution and available for plant uptake in the soils at sites south of 51°N (Table 5-1) (Mahoney et al. 2014, Westra et al. 2015, Eason et al. 2022). Subsequently the greater availability of herbicide in soil water solution at sites south of 51°N latitude likely accounts for improved weed control relative to sites north of 51°N latitude.

The individual active ingredient treatments, flumioxazin 70 gai ha^{-1}, flumioxazin 105 gai ha^{-1}, pyroxasulfone 125 gai ha^{-1}, and pyroxasulfone 150 gai ha^{-1}, performed similar to one another at locations north and south of 51°N latitude. Generally, the combination of both active ingredients, flumioxazin + pyroxasulfone 160 gai ha^{-1}, and flumioxazin + pyroxasulfone 240 gai ha^{-1} provided more consistent weed control longer into the growing season than the individual active ingredient treatments.

The main mechanism of herbicide breakdown in soil for both pyroxasulfone and flumioxazin is microbial degradation. Therefore, the amount of herbicide in the soil available for plant uptake decreases with time (Shaner 2014). This manifests visually as weed control reductions over time; later emerging weed flushes may be less effectively controlled. This effect is evident in all sites in this study as overall weed control decreased for all herbicide treatments from the 21 days after emergence evaluation to the 63 days after emergence evaluation, with the exception of the flumioxazin + pyroxasulfone 160 gai ha^{-1} + in-crop application treatment at sites north of 51°N latitude. The use of fall-applied residual herbicides in ultra-early wheat growing systems successfully replaced spring burndown applications for early-season weed control, however, our study suggests in-crop weed control remains necessary in order to reduce weed seed load into the soil seedbank.

5.5 Conclusions

The implementation of an ultra-early wheat planting system improves overall growing system stability and grain yield on the northern Great Plains but negates the use of foliar herbicides to remove weeds prior to planting, or prior to the emergence of the crop. Fall-applied residual herbicide use can allow producers to adopt ultra-early wheat planting without sacrificing early-season weed control opportunities. Our results demonstrated a weed management program in ultra-early planted wheat growing systems can safely include fall applications of flumioxazin, pyroxasulfone, and combinations of flumioxazin and pyroxasulfone to manage weeds emerging the following spring. By combining early planting, optimal seeding rates, a competitive cultivar and soil-applied residual herbicides as components of ultra-early wheat growing systems, grain yield, grain yield stability, and integrated weed management can be optimized.

5.6 Acknowledgements

The authors wish to thank many contributing technicians and staff for their effort in the completion of this study: at Agriculture and Agri-food Canada Lethbridge (Ryan Dyck, Steve Simmill, Warren Taylor, Adam Fast and many seasonal staff), at Agriculture and Agri-Food Canada Scott (Cindy Gampe, Arlen Kapiniak and many seasonal staff), and the staff at the University of Alberta (Keith Topinka, Elise Martin, Bryanna Jeske, Klaus Strenzke, Muhammad Iqbal, Fabiana Dias, Joseph Moss, Tom Keady, Katherine Chabot, Lindsay Jessup and Russell Puk). This study was funded by the Alberta Wheat Commission, project number 17AWC44A, and additional core funding was provided by the Western Grains Research Foundation. We thank the Alberta Wheat Commission, Western Grains Research Foundation and the wheat producers of Alberta for their support.

5.7 Tables

Table 5-1. Growing season descriptions, post-seeding air temperature extremes and cumulative freezing events recorded at each environment (location × year).

Location	Latitude/Longitude	Agroecological region	Soil zone, Texture	Soil organic matter (%)	pH	Average yearly precipitation* (mm)	Year	Actual precipitation (mm $year^{-1}$)	Earliest seeding date**	Number of days with air temperature below 0˚C after initial seeding date	Lowest air temperature recorded after seeding (˚C)
Edmonton, AB	53°33'N 113°29'W	Parkland	Black, Loam	9.5	5.9	446	2017	416	Apr. 7	14	-6.1
							2018	391	Apr. 27	1	-1.2
Lethbridge, AB	49°41'N 112°50'W	Western Prairies	Dark Brown, Clay Loam	4.6	8.0	380	2017	249	Mar. 20	17	-7.6
							2018	284	Apr. 23	2	-1.2
							2019	253	Apr. 2	16	-6.9
Scott, SK	52°21'N 108°49'W	Western Prairies	Dark Brown, Clay Loam	2.9	6.0	366	2017	300	Mar. 31	27	-9.4
							2018	257	Apr. 24	5	-3.1

* 1981-2010 average yearly precipitation accumulation. ** Based on 2˚C soil temperature trigger date.

Site specific soil data is gathered from on-site soil analyses.

Average and actual precipitation data for Edmonton, Alberta (University of Alberta) and Lethbridge, Alberta (Agriculture and Agri-food Canada Lethbridge Research and Development Center) sites provided by Alberta Agriculture, Forestry and Rural Economic Development, Alberta Climate information Service (ACIS) https://acis.alberta.ca.

Average and actual precipitation data for Scott, Saskatchewan (Agriculture and Agri-food Canada Scott Research Farm) sites provided by Environment and Climate Change Canada, Historical Data, https://climate.weather.gc.ca/historical_data/search_historic_data_e.html

Table 5-2. Herbicide treatment descriptions.

Treatment	Common name	Trade name	Formulation concentration & type	Applied rates (g ai ha^{-1})	In-crop Application	Manufacturer/Distributor
1	Weed free check	-	-	-	-	-
2	Untreated Check	-	-	-	-	-
3	Flumioxazin	Valtera™ Herbicide	51% WDG	70	-	Valent Canada Inc., Guelph, ON. Distributed by Nufarm Agriculture Inc., Calgary AB.
4	Flumioxazin	Valtera™ Herbicide	51% WDG	105	-	Valent Canada Inc., Guelph, ON. Distributed by Nufarm Agriculture Inc., Calgary AB.
5	Pyroxasulfone	Pyroxasulfone 85 WG Herbicide	85% WDG	125	-	K-I Chemical U.S.A. Inc. Durham, NC. Distributed by multiple companies$^{\beta}$
6	Pyroxasulfone	Pyroxasulfone 85 WG Herbicide	85% WDG	150	-	K-I Chemical U.S.A. Inc. Durham, NC. Distributed by multiple companies$^{\beta}$
7	Flumioxazin + Pyroxasulfone	Fierce™ Herbicide	76% WDG (33.5% flumioxazin + 42.5% pyroxasulfone)	160	-	Valent Canada Inc., Guelph, ON. Distributed by Nufarm Agriculture Inc., Calgary AB.
8	Flumioxazin + Pyroxasulfone	Fierce™ Herbicide	76% WDG (33.5% flumioxazin + 42.5% pyroxasulfone)	240	-	Valent Canada Inc., Guelph, ON. Distributed by Nufarm Agriculture Inc., Calgary AB.
9	Flumioxazin + Pyroxasulfone	Fierce™ Herbicide	76% WDG (33.5% flumioxazin + 42.5% pyroxasulfone)	240	1.25 L ha^{-1} Enforcer® M Herbicide 480 gai L^{-1}	Valent Canada Inc., Guelph, ON. Distributed by Nufarm Agriculture Inc., Calgary AB.

(WDG) Water dispersible granule formulation.

Valtera Herbicide and Fierce Herbicide are no longer commercially available as WDG formulations, both herbicides have been replaced by liquid suspension concentrate formulations.

$^{\beta}$Pyroxasulfone is available in western Canada in combinations with other active ingredients including flumioxazin, carfentrazone, sulfentrazone, and saflufenacil

Table 5-3. Least squares means for crop emergence, growth periods and plant counts for ultra-early seeded wheat and residual fall herbicide applications at sites north and south of 51°N latitude.

	Days to Emergence	Emergence to Anthesis Period (Days)	Anthesis to Maturity Period (Days)	Emergence to Maturity Period (Days)	Plant Count (Plants 6m row^{-1})
Sites North of 51°N Latitude (n=4)					
Planting trigger					
2°C Soil temperature	24.0	50.5	41.7	92.4	231
8°C Soil temperature	13.7	48.7	39.6	88.5	245
F Test	***	***	***	***	NS
LSD$_{0.05}$	4.9	0.6	1.0	1.3	
Herbicide treatment					
Weed free check	19.0	49.7	41.3	91.4	234
Untreated check	18.8	49.6	40.2	90.1	236
Flumioxazin 70 gai ha^{-1}	18.8	49.6	40.4	90.0	228
Flumioxazin 105 gai ha^{-1}	19.5	49.6	40.5	90.3	237
Pyroxasulfone 125 gai ha^{-1}	18.9	49.9	40.3	90.4	239
Pyroxasulfone 150 gai ha^{-1}	18.9	49.8	40.8	90.6	236
Flumioxazin + Pyroxasulfone 160 gai ha^{-1}	18.2	49.4	40.6	90.2	243
Flumioxazin + Pyroxasulfone 240 gai ha^{-1}	19.0	49.0	41.0	90.1	241
Flumioxazin + Pyroxasulfone 160 gai ha^{-1} + In-crop broadleaf herbicide application	18.8	49.6	40.8	90.7	244
F Test	NS	NS	NS	NS	NS
LSD$_{0.05}$					
Planting trigger × herbicide	NS	NS	NS	NS	NS
Sites South of 51°N Latitude (n=3)					
Planting trigger					
2°C Soil temperature	22.6	55.3	35.6	90.9	232
8°C Soil temperature	14.6	53.2	36.6	89.8	196
F Test	***	***	NS	NS	*
LSD$_{0.05}$	2.0	0.6			30
Herbicide treatment					
Weed free check	18.5	54.2	36.3	90.4	205
Untreated check	18.6	53.7	36.6	90.3	219
Flumioxazin 70 gai ha^{-1}	18.3	54.5	35.9	90.5	223
Flumioxazin 105 gai ha^{-1}	18.4	54.5	36.2	90.7	207
Pyroxasulfone 125 gai ha^{-1}	18.7	54.4	36.5	90.9	207
Pyroxasulfone 150 gai ha^{-1}	19.1	53.8	36.3	90.1	204
Flumioxazin + Pyroxasulfone 160 gai ha^{-1}	18.5	53.9	36.2	90.1	222
Flumioxazin + Pyroxasulfone 240 gai ha^{-1}	18.8	54.3	35.5	89.8	220
Flumioxazin + Pyroxasulfone 160 gai ha^{-1} + In-crop broadleaf herbicide application	18.5	54.7	35.6	90.3	218
F Test	NS	NS	NS	NS	NS
LSD$_{0.05}$					
Planting trigger × herbicide	NS	NS	*	NS	NS

(***) Significant at $P < 0.001$. (**) Significant at $P < 0.01$. (*) Significant at $P < 0.05$. (NS) Not significant. (LSD$_{0.05}$) Least significant difference at $P < 0.05$.

Table 5-4. Least squares means for crop phytotoxicity, crop uniformity and broadleaf weed control in ultra-early seeded wheat with residual fall herbicide applications north of 51°N latitude.

	Phytotoxicity (%) 14 DAE	Phytotoxicity (%) 21 DAE	Haun Growth Stage Assessment	Broadleaf Weed Control (%) 21 DAE	Broadleaf Weed Control (%) 35 DAE	Broadleaf Weed Control (%) 49 DAE	Broadleaf Weed Control (%) 63 DAE
Sites North of 51°N Latitude (n=4)							
Planting trigger							
2°C Soil temperature	1	0	6.4	74	71	71	68
8°C Soil temperature	1	1	5.7	79	77	79	76
F Test	NS	NS	**	NS	*	**	**
LSD$_{0.05}$			0.1		5	5	5
Herbicide treatment							
Weed free check	2	0	6.0	100	100	100	100
Untreated check	1	0	6.1	0	0	0	0
Flumioxazin 70 gai ha^{-1}	1	0	6.1	83	76	77	71
Flumioxazin 105 gai ha^{-1}	1	1	6.0	86	79	84	78
Pyroxasulfone 125 gai ha^{-1}	1	1	6.1	79	75	75	69
Pyroxasulfone 150 gai ha^{-1}	1	1	6.1	83	77	77	70
Flumioxazin + Pyroxasulfone 160 gai ha^{-1}	1	1	6.1	83	81	85	81
Flumioxazin + Pyroxasulfone 240 gai ha^{-1}	1	0	6.1	89	87	87	84
Flumioxazin + Pyroxasulfone 160 gai ha^{-1} + In-crop broadleaf herbicide application	2	1	6.0	86	89	92	96
F Test	NS	NS	NS	***	***	***	***
LSD$_{0.05}$				8	8	6	6
Planting trigger × herbicide	NS	NS	NS	NS	NS	NS	NS

(DAE) Days after crop emergence. (***) Significant at $P < 0.001$. (**) Significant at $P < 0.01$. (*) Significant at $P < 0.05$. (NS) Not significant. (LSD$_{0.05}$) Least significant difference at $P < 0.05$.

Table 5-5. Least squares means for crop phytotoxicity, crop uniformity and broadleaf weed control in ultra-early seeded wheat with residual fall herbicide applications south of 51°N latitude.

	Phytotoxicity (%) 14 DAE	Phytotoxicity (%) 21 DAE	Haun Growth Stage Assessment	Broadleaf Weed Control (%) 21 DAE	Broadleaf Weed Control (%) 35 DAE	Broadleaf Weed Control (%) 49 DAE	Broadleaf Weed Control (%) 63 DAE
Sites South of 51°N Latitude (n=3)							
Planting trigger							
2°C Soil temperature	2	2	4.8	85	82	80	75
8°C Soil temperature	2	2	4.7	85	82	80	74
F Test	NS	NS	NS	NS	NS	NS	NS
LSD$_{0.05}$							
Herbicide treatment							
Weed free check	2	2	4.6	100	100	100	100
Untreated check	2	2	4.8	0	0	0	0
Flumioxazin 70 gai ha^{-1}	2	2	4.7	94	90	88	77
Flumioxazin 105 gai ha^{-1}	2	2	4.6	94	91	88	78
Pyroxasulfone 125 gai ha^{-1}	2	2	5.0	95	89	86	81
Pyroxasulfone 150 gai ha^{-1}	2	2	4.8	96	91	89	83
Flumioxazin + Pyroxasulfone 160 gai ha^{-1}	2	2	4.8	96	91	88	85
Flumioxazin + Pyroxasulfone 240 gai ha^{-1}	2	2	4.7	98	94	93	85
Flumioxazin + Pyroxasulfone 160 gai ha^{-1} + In-crop broadleaf herbicide application	2	2	4.7	94	91	90	83
F Test	NS	NS	NS	***	***	***	***
LSD$_{0.05}$				3	5	5	7
Planting trigger × herbicide	NS	NS	NS	NS	NS	NS	NS

(DAE) Days after crop emergence. (***) Significant at $P < 0.001$. (**) Significant at $P < 0.01$. (*) Significant at $P < 0.05$. (NS) Not Significant. (LSD$_{0.05}$) Least Significant Difference at $P < 0.05$

Table 5-6. Least squares means for grain yield and grain quality parameters for ultra-early seeded wheat and residual fall herbicide applications at sites north and south of 51°N latitude.

	Yield (Mg ha^{-1})	Protein (%)	Test Weight (kg hL^{-1})	Thousand Kernel Weight (g)
Sites North of 51°N Latitude (n=4)				
Planting trigger				
2°C Soil temperature	4.17	11.6	81.7	31.4
8°C Soil temperature	4.27	11.2	82.7	31.9
F Test	NS	NS	***	*
LSD$_{0.05}$			0.5	0.5
Herbicide treatment				
Weed free check	4.26	11.4	82.5	32.3
Untreated check	4.01	11.3	82.1	31.0
Flumioxazin 70 gai ha^{-1}	4.28	11.3	82.3	31.5
Flumioxazin 105 gai ha^{-1}	4.19	11.4	82.2	31.1
Pyroxasulfone 125 gai ha^{-1}	4.34	11.4	82.0	32.0
Pyroxasulfone 150 gai ha^{-1}	4.19	11.4	82.0	31.7
Flumioxazin + Pyroxasulfone 160 gai ha^{-1}	4.15	11.5	82.0	31.3
Flumioxazin + Pyroxasulfone 240 gai ha^{-1}	4.26	11.5	82.1	32.0
Flumioxazin + Pyroxasulfone 160 gai ha^{-1} + In-crop broadleaf herbicide application	4.30	11.5	82.5	32.2
F Test	*	NS	NS	**
LSD$_{0.05}$	0.19			0.8
Planting trigger × herbicide	NS	NS	NS	NS
Sites South of 51°N Latitude (n=3)				
Planting trigger				
2°C Soil temperature	2.97	12.5	77.0	29.2
8°C Soil temperature	2.52	12.6	75.9	28.2
F Test	**	NS	**	*
LSD$_{0.05}$	0.24		0.7	0.9
Herbicide treatment				
Weed free check	2.72	12.6	76.4	28.3
Untreated check	2.70	12.4	76.5	28.4
Flumioxazin 70 gai ha^{-1}	2.86	12.3	76.6	28.7
Flumioxazin 105 gai ha^{-1}	2.83	12.4	76.9	29.1
Pyroxasulfone 125 gai ha^{-1}	2.63	12.4	76.6	28.8
Pyroxasulfone 150 gai ha^{-1}	2.73	12.6	76.3	28.7
Flumioxazin + Pyroxasulfone 160 gai ha^{-1}	2.75	12.6	76.0	28.3
Flumioxazin + Pyroxasulfone 240 gai ha^{-1}	2.67	12.8	76.0	28.6
Flumioxazin + Pyroxasulfone 160 gai ha^{-1} + In-crop broadleaf herbicide application	2.82	12.4	77.0	29.1
F Test	NS	NS	*	NS
LSD$_{0.05}$			0.6	
Planting trigger × herbicide	NS	NS	*	NS

(***) Significant at $P < 0.001$. (**) Significant at $P < 0.01$. (*) Significant at $P < 0.05$. (NS) Not significant. (LSD$_{0.05}$) Least significant difference at $P < 0.05$.

5.8 Figures

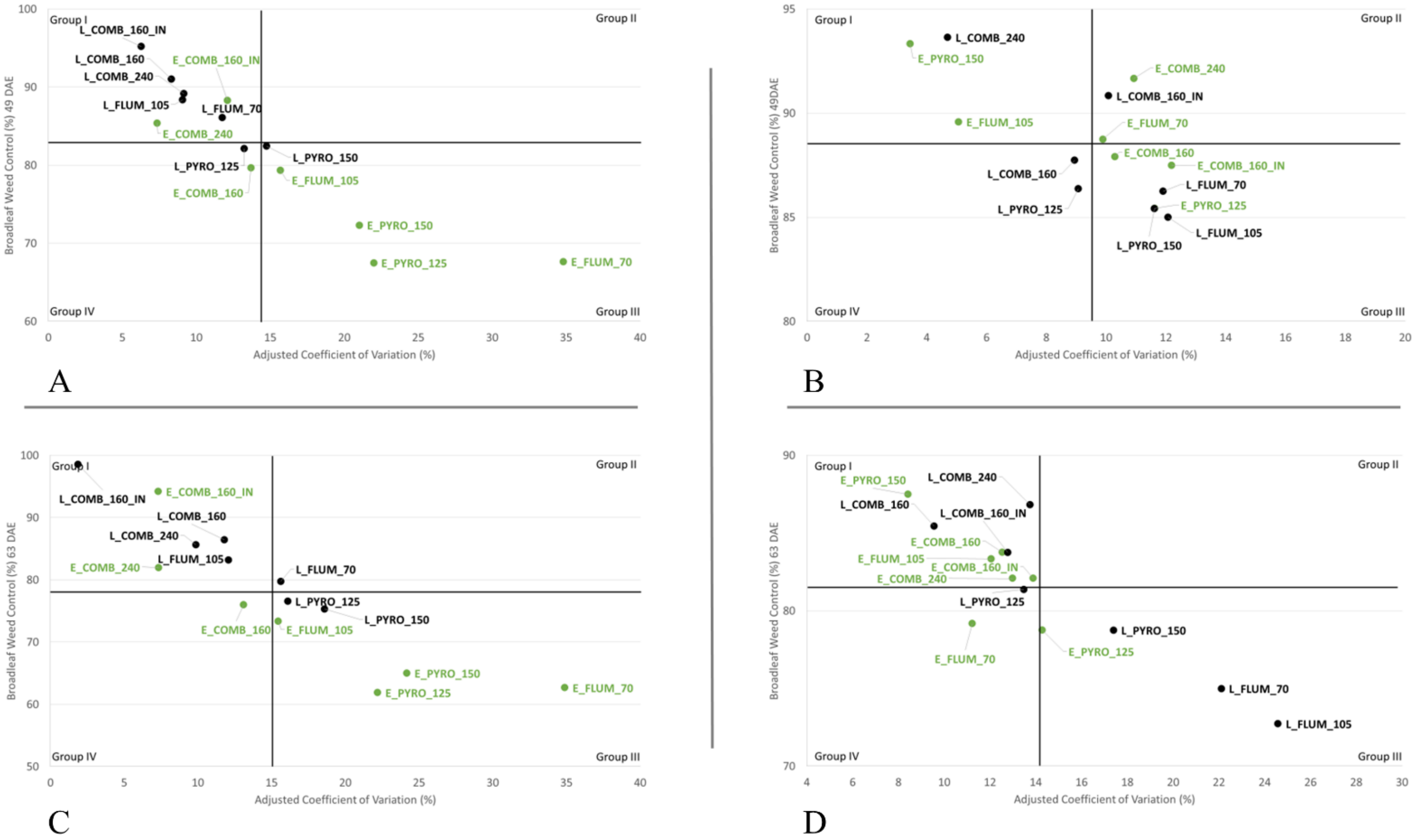
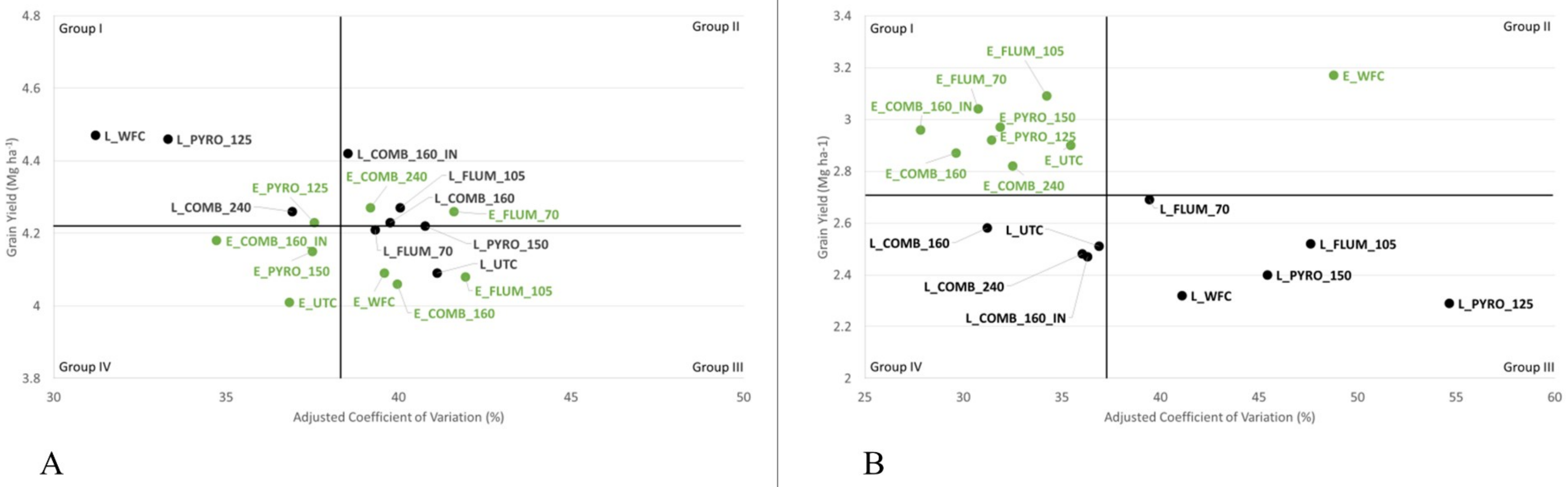


Figure 5-1. Biplot summarizing average broadleaf weed control means vs. adjusted coefficient of variation (aCV) for each planting date and herbicide treatment at 49 days after emergence (DAE) for **(A)** sites north of 51°N latitude, **(B)** sites south of 51°N latitude and at 63 DAE for **(C)** sites north of 51°N latitude and **(D)** sites south of 51°N latitude.

Abbreviations as follows: (I) The first letter represents the planting date (**E** – ultra-early planting triggered at a soil temperature of 2°C. **L** – later planting triggered at a soil temperature of 8°C.) (II) The next letters denote the herbicide treatment (**UTC** – untreated check. **WFC** – weed free check. **FLUM** – flumioxazin. **PYRO** – pyroxasulfone. **COMB** – flumioxazin + pyroxasulfone.) (III) The next numbers, if present, represent the amount of active ingredient in the treatment in gai ha^{-1}. (IV) The final letters (**IN**), if present, represent the presence of an in-crop herbicide application. Colours are a visual representation of planting date: **green** – ultra-early, **black** – later planting. Grouping categories are divided by a vertical line representing the mean aCV and a horizontal line representing the mean grain yield: Group I: high mean, low variability; Group II: high mean, high variability; Group III: low mean, high variability; Group IV: low mean, low variability.



A

B

Figure 5-2. Biplot summarizing grain yield means vs. adjusted coefficient of variation (aCV) for each planting date and herbicide treatment at sites **(A)** north of 51°N latitude and **(B)** south of 51°N latitude.

Abbreviations as follows: (I) The first letter represents the planting date (**E** – ultra-early planting triggered at a soil temperature of 2°C. **L** – later planting triggered at a soil temperature of 8°C.) (II) The next letters denote the herbicide treatment (**UTC** – untreated check. **WFC** – weed free check. **FLUM** – flumioxazin. **PYRO** – pyroxasulfone. **COMB** – flumioxazin + pyroxasulfone.) (III) The next numbers, if present, represent the amount of active ingredient in the treatment in gai ha^{-1}. (IV) The final letters (**IN**) if present, represent the presence of an in-crop herbicide application. Colours are a visual representation of planting date: **green** – ultra-early, **black** – later planting. Grouping categories are divided by a vertical line representing the mean aCV and a horizontal line representing the mean grain yield: Group I: high mean, low variability; Group II: high mean, high variability; Group III: low mean, high variability; Group IV: low mean, low variability.

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6.0 Best management practices for producer-level implementation of an ultra-early wheat growing system and original contributions to knowledge

6.1 Introduction

Successful adoption of an ultra-early spring wheat growing system by producers on the northern Great Plains of Canada induces few costs beyond current wheat production practices and provides benefits to the producer in the form of greater grain yield and greater grain yield stability. However, some best management practices require modest increases in management intensity and changes in the time of implementation of current on-farm practices. Careful planning is required to maximize the benefits of switching to ultra-early wheat planting. This section summarizes some of the key considerations for producers and highlights management differences between current conventional-timed wheat growing systems and ultra-early wheat growing systems. This chapter is based on extensive questions from Alberta producers who were early adopters of ultra-early wheat planting, and is written for the benefit of future ultra-early wheat growing system adopters in western Canada.

6.2 Best management practices for producer-level implementation of an ultra-early wheat growing system

6.2.1 Field selection and regional response

An inherent part of an ultra-early wheat planting system is that planting occurs in spring earlier than any other crop on the producer's farm or in the region. Initial planting may occur more than a month earlier than traditional wheat planting dates, and is triggered by soil temperature rather than long-term weather conditions or calendar date. As such, fields selected for initial planting should be selected based on early drainage, accessibility, topography and primary relief, ensuring planting can physically begin when soil temperature triggers are reached without sacrificing large sections of the field due to impassable conditions.

Predominant soil type has an effect on ultra-early planting initiation and field accessibility; brown and dark-brown soils tend to support ultra-early planting systems more effectively, and return more consistent results than black soil zone locations. This is primarily a result of the brown and dark brown soil zone regions having earlier snow cover melt, lower spring soil moisture, lower moisture holding capacity of the soils, and earlier soil temperature increase to 0°C, combined with slower progression in soil temperature increase after reaching 0°C. Black soil zones tend to reach 0°C later in the spring, and could be impassable for planting equipment at that time due to soil saturation from snow melt. Later snow melt, higher water holding capacity and greater solar radiation at the time of reaching 0°C mean black soils rapidly progress from 0°C to 10°C relative to the dark brown and brown soils. This reduced time period may limit the opportunity for the benefits of ultra-early seeding to be realized in the black soil zones under current climate conditions. Despite the overall benefits of the growing system potentially being limited in the black soil zone, no negative effect of ultra-early wheat planting was observed.

6.2.2 Soil temperature determination and planting triggers

Soil temperatures should be determined using a soil temperature probe placed to read temperature at 5 cm depth in a representative location in the field. In order to maintain consistency, soil temperatures should be recorded in the same location at the same time of day each day (10:00 AM recommended), as planting trigger soil temperatures approach. This consistency helps avoid confounding readings due to high surface soil temperatures later in the day. The recommended optimum planting period is between soil temperatures of 2°C and 6°C, however, no negative grain yield affect was noted between 0°C and 8°C. Producers with large areas to plant may wish to use 0°C as their initial trigger temperature rather than the optimum recommended soil temperature of 2°C in order to complete planting over a greater area prior to reaching soil temperatures of 10°C. Reductions in grain yield and grain yield stability were noted for plantings occurring after soil temperatures reached 10°C. Planting when the soil surface was below 0°C resulted in frozen clods of soil moving with planter openers and insufficient soil packing back into the seed row, thus reducing seed to soil contact and planting uniformity. Planting prior to soil temperatures reaching 0°C is not recommended.

6.2.3 Planting rate and depth

Producers shifting from conventional-timed wheat planting systems to an ultra-early planting system should increase their planting rate to the optimum planting rate for their selected variety and wheat production in their region. An optimum planting rate of 400 viable wheat seeds m^{-2} resulted in greater grain yield and greater grain yield stability at any planting timing relative to a conventional planting rate of 200 viable wheat seeds m^{-2}. The use of optimum planting rates is identified as the most important management tactic to increase the success and value of an ultra-early wheat planting system for the producer. Planting depth did not affect grain yield, however shallower planting depth (2.5 cm versus 5 cm) tended to improve grain yield stability.

6.2.4 Wheat variety selection

Canadian hexaploid spring wheats from multiple market classes were evaluated in ultra-early planting systems; evaluations were completed using sub-optimal planting rates in order to increase stress on the growing system and more readily identify negative responses within cultivars and between Canadian wheat market classes. Despite sub-optimal conditions, no differential in individual variety performance or class performance was recorded between ultra-early and conventional planting times. The broad adaptation of Canadian hexaploid wheat varieties and classes to ultra-early planting suggests producers need not select varieties for cold tolerance characteristics, but rather selection may be primarily based on regional adaptation, grain yield, grain quality and end-use characteristics. Durum wheat and other cereals including barley, spring triticale and oats were not evaluated and therefore a recommendation for ultra-early planting cannot be extended to these cereal crops at this time.

6.2.5 Crop protection

Ultra-early wheat planting means spring planting occurs prior to the emergence of weeds, and the planted wheat is required to endure cold, damp soil conditions for longer periods of time prior to germination and emergence. Important considerations for producers shifting to ultra-early wheat planting systems are the use of fungicidal, or fungicidal and insecticidal, seed treatments to reduce the negative effects of seed and soil borne pathogens on germination, vigor and plant survival (Beres et al. 2016, Turkington et al. 2016, Ford et al. 2010). Pre-emergent spring applications of herbicides may not be possible due to the absence of early germinating weeds; this can negatively affect overall weed control in the growing system. Producers should consider the use of fall-applied residual herbicides in fields intended to be planted ultra-early. Fall-applied residual herbicides can reduce weed populations the following spring until subsequent herbicide applications are applied in-crop, or until wheat canopy closure and crop competition can overcome spring/summer emerging weeds. Producers should remain vigilant as ultra-early planted wheat will reach important physiological stages earlier in the season than conventional-timed plantings, thus tasks which can be limited to specific crop growth stages such as fungicide applications may need to be completed earlier in the season. Similarly, some common management practices such as control of wheat midge may not be required if susceptible crop development stages pass prior to pest development.

6.3 Future research

The recommendations of this research are limited to Canadian hexaploid wheat varieties. Durum wheat (tetraploid genome ($2n=4x=28$; AABB)) was planted on approximately 25% of the total area planted to wheat in Canada in 2019 and is predominantly grown in the brown and dark brown soil regions of western Canada (Statistics Canada 2021). The benefits of ultra-early planting of hexaploid wheat tended to be the greatest in the soil zones where durum wheat is commonly grown. Future research to establish the tolerance of durum wheat varieties to ultra-early planting and evaluate the viability of an ultra-early planting system for durum production on the northern Great Plains would be beneficial for durum wheat producers. A project evaluating ultra-early durum wheat growing systems is underway, led by Dr. Brian Beres of Agriculture and Agri-Food Canada - Lethbridge.

Similarly, the tolerance of other cereal grains to ultra-early planting systems on the northern Great Plains has not been evaluated. Spring barley, spring triticale and oats may respond similarly to wheat to ultra-early planting. Comparisons across species to identify the cereals that realize the greatest benefit and are the most stable when planted ultra-early could lead to further changes in conventional planting times, crop rotations, and crop sequences. Ultra-early planting of short-season cereals could create an opportunity for double cropping or early cover crop establishment in limited parts of western Canada.

This research did not find the point at which early planting leads to a significant decline in grain yield. The earliest planting in the studies was intentionally limited to 0°C by the experimental designs. Earlier planting into colder soils was additionally limited by the ability of the planting equipment used in these studies to successfully penetrate frozen soil and sufficiently close seed row furrows in frozen soil. Specialized planting equipment suitable for planting into frozen soil may allow further evaluation of early planting and determination of how early in the spring planting can occur before grain yield or grain yield stability are negatively affected. Additional evaluations of ultra-early spring planting compared with frost seeding and dormant seeding systems would be beneficial to determine superior agronomic systems for cereal production (Thilakaranthna et al. 2017, Austenson, 1972).

The opportunity exists to more intensely investigate optimization of ultra-early wheat growing systems by manipulating components of G × E × M interactions within the growing system. While cold tolerant genetics did not impact grain yield stability in the current research, ultra-early planting may allow the use of longer season, higher yield potential varieties in some growing regions. Similarly, ultra-early growing systems combined with newly developed wheat cultivars with improved heat and drought tolerance characteristics may lead to synergistic increases in growing system grain yield or grain yield stability. Several agronomic management tactics and system inputs could be further evaluated within ultra-early planting systems as a means to intensify management and improve grain yield or grain yield stability, leading to a narrowed yield gap. Initial consideration may be given to macro and micro nutrient optimization in ultra-early planting conditions, and managing the length and timing of the transition between vegetative and reproductive growth periods using photoperiod sensitive and insensitive wheat lines.

The initial proof of concept and optimization of ultra-early hexaploid wheat growing systems for the northern Great Plains presented here leaves significant opportunity for further systems-based improvements. As global average temperatures warm, and atmospheric CO_2 concentrations increase, the northern Great Plains region is in a unique position to potentially realize grain yield increases rather than temperature driven grain yield decreases. Shifting planting earlier and taking advantage of increased growing degree day accumulation and water use efficiencies while avoiding higher temperatures during sensitive physiological periods are tactics implemented in ultra-early growing systems that will increase in importance and relevance in the next three decades as average daily temperatures increase. The beneficial effects of these tactics can be further optimized when paired with appropriate new management practices and improved genetics. Similar to the success of Kirkegaard and Hunt (2010), optimizing agronomics and genetics within an ultra-early wheat growing system should be a key focus of future research and may lead to the discovery of synergistic interactions within the system that can dramatically increase grain yield and growing system stability despite environmental challenges.

6.4 Original contributions to knowledge

Reported global reductions in cereal grain yields due to increased global average temperature combined with increasing global populations peaking near 2050 create an immediate need to increase cereal grain yield potential and reduce the yield gap between realized on-farm grain yield and potential yield. The responses in grain yield, grain yield stability and growing system resiliency to shifting spring wheat planting earlier in the season on the northern Great Plains and standardizing the start of planting using soil temperature rather than calendar date, were not known. Similarly, the ability of conventional Canadian hexaploid spring wheat cultivars to survive ultra-early planting, and which agronomic management practices would help maintain or increase grain yield in such a system, were unknown. Therefore, it was necessary to conduct proof of concept studies to first evaluate the performance of current commercial wheat varieties and specially developed cold tolerant wheat varieties in ultra-early planting systems. Based on superior performance of commercial wheat varieties when planted ultra-early compared to conventional planting times, basic agronomic practices were evaluated to build a suite of recommendations to support the successful adoption of ultra-early wheat growing systems at the producer level on the northern Great Plains.

Chapter one in this thesis is a review of the development of current wheat production systems on the northern Great Plains following the evolution of the management of G × E × M interactions in wheat production, from the first cultivation of wheat in western Canada, through to the modern intense management systems used today. The review discusses key discoveries, challenges, technologies, and management tactics that have, or will, dramatically influence the growth and capacity of wheat production in western Canada, and relates them to their impact on one or multiple factors within G × E × M interactions. To my knowledge this is the first review to evaluate historical development of wheat production in western Canada in the context of continual evolution in management of G × E × M.

The study presented in chapter two serves as the initial proof of concept for evaluation of a conventional Canadian hexaploid spring wheat variety in ultra-early planting systems. Other early planting systems including frost seeding and dormant seeding have been evaluated previously, but to my knowledge no study has ever evaluated planting of wheat based on soil temperature and beginning immediately at ground thaw. In the study a common Canadian western red spring wheat cultivar 'AC Stettler' was planted at multiple soil temperatures from 0°C to 10°C and compared to cold tolerant spring wheat lines, previously evaluated for superior survival in cold conditions at the University of Guelph by Larsen (2012). Similar to the cold tolerant lines, AC Stettler had greater grain yield and better grain yield stability when planted ultra-early than when planting was delayed until soil temperatures reached 10°C. The performance of AC Stettler in this initial evaluation of ultra-early wheat planting on the northern Great Plains enabled the subsequent development of ultra-early wheat growing systems based on current wheat varieties rather than requiring the co-development of spring wheat lines with specialized cold tolerant traits. The absence of a unique cold tolerance requirement for wheat varieties used in ultra-early wheat growing systems reduces adoption hurdles for a producer looking to engage in ultra-early planting and removes the need to devote additional cost and time to develop commercially viable cold tolerant varieties. No previous study has evaluated planting of Canadian western red spring wheat as early in the season as the studies presented here.

The development of a new growing system in wheat which is based on significant changes to traditional planting time necessitated evaluation of the effects of basic agronomic management tactics in the new system relative to conventional practices. In chapter three we integrated further evaluation of ultra-early planting (four plantings between 0°C and 10°C soil temperatures) with manipulations of sowing density and sowing depth in order to determine if grain yield and grain yield stability of an ultra-early wheat growing system could be improved with optimal agronomics. The beneficial grain yield effects of optimum sowing rates have been evaluated by multiple previous studies, but never when spring wheat was planted ultra-early and never in comparison with conventional planting times. Similarly, studies regarding sowing depth have been conducted previously, but never in ultra-early planting systems in western Canadian growing conditions. Thus, in addition to planting time, this study evaluated two sowing densities (conventional and optimum) and two sowing depths (2.5 cm and 5cm). The findings of this study substantiated the results of the study detailed in chapter two regarding the beneficial effect of ultra-early planting on grain yield, and grain yield stability. Furthermore, the use of an optimal sowing rate significantly increased grain yield and grain yield stability. The use of optimum planting rates emerged as the most important management tool to increase both grain yield and grain yield stability in ultra-early wheat growing systems. Planting depth exhibited a modest increase in grain yield stability when shallower planting depths were used, but did not affect grain yield. Thus, the combined results of the first two chapters defined the unique components of an ultra-early wheat growing system: specialized wheat varieties are not required, begin planting at soil temperatures as low as 0°C - 2°C, attempt to plant at an optimum sowing density for the wheat variety used and the production region (400 viable seeds m^{-2} can be considered a minimum), and err toward a more shallow planting depth (2.5 cm).

While the initial studies reported in chapters two and three focused on the proof of concept of ultra-early wheat planting and basic agronomy, chapters four and five evaluated specific challenges that will be faced by producers adopting an ultra-early wheat growing system. In the initial studies we evaluated cold tolerant wheat lines and one common Canadian western red spring wheat variety, finding no differential in variety performance in ultra-early planting systems. In chapter four we expanded our evaluation of Canadian wheat varieties in ultra-early planting systems to include multiple varieties from multiple Canadian wheat market classes. Varieties were selected to account for the greatest current planted area in western Canada and to be representative of as much genetic variation within the designated wheat market classes as possible. This is the first and largest screen of Canadian wheat varieties in an ultra-early planting system. The broad adaptation of AC Stettler when planted ultra-early was maintained across an additional eight Canadian wheat varieties from four Canadian spring wheat marketing classes. Grain yield was not affected by ultra-early or conventional planting time for any individual cultivars planted. However, the grain yield stability of every cultivar was greater when planted ultra-early relative to the conventional planting time despite the experiment being conducted at a sub-optimal sowing rate.

The study in chapter five addressed questions regarding changes in weed management strategies in ultra-early wheat planting systems. The inability of growers to make a pre-seed herbicide application on emerged weeds prior to ultra-early planting removes an important weed management tool from current weed management programs. In order to avoid the loss of this early-season weed control opportunity in an ultra-early wheat growing system we evaluated the use of fall-applied residual herbicides in ultra-early wheat growing systems. Residual herbicides are registered for use in the fall prior to planting spring wheat the next spring, but have never been evaluated when spring wheat planting would occur as early as in an ultra-early planting system. Planting into cold, wet, herbicide treated soil the following spring could increase the potential of seedling injury, mortality or reduced vigor, leading to a decrease in growing system stability. The tolerance of spring wheat to flumioxazin, pyroxasulfone and combinations thereof has never been evaluated when spring planting is completed ultra-early and the plants experience cold, wet soils for an extended period. Spring wheat tolerance to the fall-applied residual herbicides was exceptional, and led to an increase in weed control and growing system stability in the brown and dark brown soil zones. This study demonstrated for the first time that fall-applied soil-residual herbicides were safe for use when wheat planting is completed ultra-early the following spring, and that proper weed control can increase the growing system stability of an ultra-early wheat growing system.

The overarching goal of this thesis was the development of a modified growing system for spring wheat on the northern Great Plains that would increase the resiliency of the current growing system to future changes in the climate. The end result has been the development of a unique set of recommendations built to successfully shift current wheat production systems to ultra-early growing systems. Ultra-early wheat growing systems will provide immediate benefits to the adopting producer in the form of increased grain yield and increased grain yield stability relative to current practices. The benefits of producer adoption of ultra-early planting, and the management recommendations provided herein, should continue to increase with time as average daily temperatures and atmospheric CO_2 concentration continue to increase.

The literature review provides a history of continual adaptation of wheat production in western Canada in response to the environmental and historical challenges faced by the predominant wheat growing systems of the time, as well as a review of anticipated future challenges to wheat production in Canada. The four data chapters culminate in the sixth chapter with a set of best management practices for producer implementation of an ultra-early wheat growing system on the northern Great Plains.

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