Evaluation and Comparison of the Agronomic Traits of 100 Wheat Cultivars Grown in Western Canada

By

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

Master of Science
in
Plant Science

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Abstract

Breeding efforts have been crucial in solving the challenges of wheat production in western Canada. This study evaluates and compares the agronomic traits of plant height, days to heading, lodging, days to maturity, grain yield, disease resistance, test weight, thousand kernel weight, and protein content of 100 cultivars grown in western Canada in order to monitor the effectiveness of breeding programs. The results indicate the positive selection of breeding programs for most of the traits. Modern wheat cultivars have higher grain yield, protein content, earlier days to maturity and improved disease resistance.

Preface

This thesis is an original work by Neshat Pazooki Moakhar. The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board, Project Name "Evaluation and Comparison of the Agronomic Traits of 100 Wheat Cultivars Grown in Western Canada", No. 12345, 24/03/2014.

The agronomic traits data from the Kernen, St. Albert and Edmonton fields used in this research were collected by the University of Saskatchewan, the University of Alberta and by Neshat Pazooki Moakhar respectively. The nursery data from Lethbridge and Creston fields were collected by Agriculture Canada in Lethbridge. The nursery data from Edmonton was collected by Neshat Pazooki Moakhar. Statistical data analysis of this work was performed by Dr. Muhammad Iqbal from cereal research group supervised by Prof. Dean Spaner. The literature Review (chapter 1), Materials and Methods, data collection (Chapter 2), data presentation in Results section (Chapter 3) as well as data interpretation and conclusions presented in Discussion section (Chapter 4) are my original work. No part of this thesis has been previously published.

Acknowledgment

This M. Sc. thesis has been carried out since I joined the cereal research group at the University of Alberta. I have worked with a great number of people who have contributed in various ways to the research in this thesis and deserve special mention. It is a pleasure to convey my gratitude to them with my humble acknowledgment.

I would like to express my gratitude to my supervisor Prof. Dean Spaner for his supervision and advice from the early stages of this research. I obtained valuable experience throughout the work as well as adding significantly to my knowledge about wheat. Above all, he provided me with constant encouragement and support and helped me to understand the different scientific aspects of this research and to develop new ideas which have enriched my growth as a researcher.

I would like to thank my thesis committee member, Dr. Stephen Strelkov for his valuable teachings during the course “Principles of Plant Pathology”.

My special thanks to my colleague, Mr. Klaus Strenzke, who never hesitated to help me whenever I called on him.

I would like also to acknowledge the “University of Saskatchewan” and “Agriculture Canada” for their data collections and submission to me which enabled drawing a more clear picture of wheat properties in this research.

I gratefully acknowledge, Dr. Muhammad Iqbal, my colleague who helped me to understand different aspects of this research as well as due to his efforts in statistical analysis of the data.

Special thanks to my nice colleagues, Ms Hua Chen, Dr. Atif Kamran, Mr. Muhammad Asif, Ms Fabiana Dias, Mr. Ivan Adamyk, Mr. Graham Collier and Mr. Hirushi Kubota for their supports throughout this research.

Last of all but not least, I would like to thank my family especially my mother Nahid and my husband Amir for their support and encouragement which helped me carry out this research.

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1. An introduction to wheat

Wheat (*Triticum aestivum* L.) is an annual grass. It is self-pollinated and belongs to the family of *Poaceae*, genus *Triticum* and the most commonly grown species is T. *aestivum* or common bread wheat. Einkorn (*T. monococcum*) and Emmer (*T. dicoccum*) were the primary species of wheat from which today's wheat originated. Wheat is one of the most important cereals in the world in terms of production and grown area. Countries such as China, USA, Russia, India, Canada, Australia, France, Pakistan, Turkey and Argentina are the major wheat producers in the world. Wheat originated in the Fertile Crescent region of the Near East around 8000 B.C. Wheat has been grown in most regions of the world except in the lowland tropics. It shows excellent adaptation to climate and geographical regions since different cultivars of wheat grow at altitudes from sea level to 3500 m and between latitudes 60° North and South (Winch, 2006). The most commonly produced wheat species are bread wheat (*T. aestivum* L.), and durum wheat (*T. turgidum* L.) (Pingali 1999).

The optimum temperature for wheat germination is 20-28 °C and the minimum temperature is 2-4 °C. Its seedlings normally emerge after 5-6 days of planting and seed dormancy is short. Soil used for wheat growth should be fertile; medium-heavy textured, well drained and should have good lime content. Due to lodging problems, arising from declining value of wheat straw, breeders tend to produce dwarf (<60 cm tall) or semi dwarf (60-90 cm tall) wheat cultivars. Normal depth of wheat sown is 2.5-5 cm, but in dry soil it is often planted in 8-10 cm. Deeply sown wheat produces fewer tillers (Curtis et al. 2002).

There are several wheat classifications depending on specific characteristics. Based on wheat hardness, there are two types of wheat grains known as hard grain cultivars and soft grain cultivars. Hard grain cultivars grow in dry areas, have vitreous endosperm, have 11-15% protein content (strong), and are mainly used for bread. Soft grain cultivars grow in humid areas, have mealy endosperm, have 8-10% protein content (weak) and are used for baking cakes, biscuits, and pastry (Winch, 2006).

Another classification of wheat is based on the season the crop is grown: spring wheat or winter wheat. Spring wheat, as the name implies, is usually planted in the spring. Spring cultivars do not require a cold period for vernalization. They need about 100 frost free-days and when the day length becomes long they flower and in the late summer they mature. Meanwhile, winter cultivars of wheat are planted in autumn in temperate regions and grow and develop into young plants in the vegetative phase during winter time, and continue their growth in early spring. Their heading time is delayed until they have a period of cold winter temperatures (0 to 5 °C) to be vernalized (Iqbal et al. 2006).

1.1. Wheat in Canada

Wheat is the major crop grown in Canada. In 1928 Newman described wheat as having an important role in the industrial and commercial life of Canada; building the economic structure of the three prairie provinces. Alberta, Saskatchewan and Manitoba produce about 95% of Canadian wheat (McCallum and DePauw 2008). Since a large proportion of western Canadian wheat is exported, wheat has had a large impact on the financial and cultural development of western Canada (Rawlinson and Granatstein 1997).

Canada produces about 33.0 million tonnes of wheat annually, with 24 m t consisting of spring hexaploid, 6.0 million tones consists of durum wheat and only 4 million tonnes of winter wheat. Because of limited domestic consumption, about 70% of hexaploid wheat and 80% of durum wheat are exported to 70 countries across the world. These exports generated 3.5 to 5 billion CDN annually by 2007 for Canada. Canadian wheat is classified according to different end use suitability parameters such as grain protein concentration; gluten strength and kernel color (DePauw et al. 2011).

There are three main types of wheat produced in western Canada, spring hexaploid wheat (*Triticum aestivum L.)*, winter hexaploid wheat (*Triticun aestivum L*.) and durum wheat (*Triticum turgidum*). Due to the long and severe winter and short and hot summer in the prairie provinces, spring wheat is the predominant type cultivated. Spring hexaploid, durum wheat and winter wheat consist of 69%, 23% and 8% of the total wheat production in Canada (DePauw et al. 2011). Wheat is also produced in eastern Canada, mainly in southern Ontario, where approximately 50% is used domestically (Dexter et.al. 2006).

Southern Alberta and Saskatchewan crops are prone to drought conditions due to the limited rainfall and high evaporation rate (Cutforth et al. 1993). Wheat grows in areas of eastern Saskatchewan and Manitoba are subjected to severe infestations of rusts and some other diseases (Samborski et al. 1986).

1.1.1. Wheat classifications in western Canada and grading system

Western Canadian wheat is classified by the Canadian Grain Commission (CGC), a department within Agriculture and Agri-Food Canada (AAFC) that oversees quality assurance of Canadian crops. There are 8 classes of wheat in western Canada which are classified based on merit according to disease resistance, agronomic performance and processing quality. Grading factor is one of the most important factors determining the processing value of wheat and is associated with wheat physical condition (Dexter and Tipples 1987). Physical condition is determined mainly by growing conditions which can affect the edibility and end-use quality of common wheat, like cultivars of the Canadian western red spring class (Dexter et al,. 2006).

1.1.2. Canadian spring wheat classes

Canadian wheat cultivars are classified into eight different classes according to their characteristics such as kernel shape and color, embryo size and shape, and also baking characteristics. Table 1-1 summarizes different characteristics of these classes. Cultivars of Canada Western Red Spring (CWRS) class are widely grown in western Canada (DePauw et al. 2011).

1.2. Wheat breeding

During the past 100 years, wheat yield has significantly increased due to the improvement of varietal performance as well as applications of chemical fertilizers, herbicides and pesticides (Ceccarelli 1996). Global wheat breeding efforts over the last 50 years have sought to accomplish two major goals which are increasing grain yield and improving the quality of wheat cultivars. Other breeding programs around the world are increasing disease and lodging resistance, improving the response of wheat cultivars to fertilizers, and developing new cultivars which can adapt to different agronomic environments (Curtis et al. 2002).

1.2.1. Wheat breeding in Canada

Since wheat is one of the most important sources of plant protein in our diet, and is a cornerstone of Canadian agriculture, it has been researched extensively. Wheat producers in western Canada face a number of production challenges and to solve them, breeding efforts have been quite extensive. Major goals of wheat breeding program have been to increase the grain yield and improve the end-use quality of Canadian wheat. Breeding programs in Canada generally include two components: agronomic improvements in cultivars, and improvements of end-use quality for prairie wheat (McCaig and De Pauw 1995).

Important agronomic traits are high yield, test weight, maturity, plant height, lodging resistance, disease resistance, etc. Early maturity is one of the important traits since the growing season in the northern regions of Western Canada is short (Iqbal et al. 2006). Sometimes late-maturing cultivars are badly damaged due to frost. AC Splendor (CWRS) is an early-maturing cultivar grown in the northern regions.

Improvements in the end-use quality include increasing protein concentration, gluten strength, milling yield, enhancing bread making quality and reducing susceptibility to preharvest sprouting (McCaig and DePauw 1995). To increase the protein content of cultivars, the high protein accumulation gene Gpc-B1, originally derived from *Triticum turgidum* L. *dicoccoides* (Humphreys et al. 1998), was bred into CWRS cultivars Lillian and Somerset (registered in 2005) and the CWES cultivar Burnside (registered in 2004). Resistance to pre-harvest sprouting also has been a major improvement in many wheat cultivars in western Canada. In 1980, Columbus was the first cultivar with high resistance to pre-harvest sprouting followed by AC Domain in 1993, and many recent cultivars (McCaig and De Pauw 1995).

Improvement in disease resistance, especially rust resistance, has been a major achievement of wheat breeding in Western Canada. Extensive losses due to stem rust led to improved genetic resistance, which was durable and provided protection over many years. Another important disease during the period of wheat cultivation in western Canada is leaf rust. Leaf rust resistance genes have provided important protection although sometimes they have not been durable (McIntosh et al. 1995).

1.2.2. Breeding of the Hard Red Spring Wheat in western Canada

A main reason for the success of wheat production on the Prairies is related to the success of wheat breeding programs in Canada (Morrison 1960). The major goal of breeding programs is to increase grain yield. However, this important trait has been difficult to reach as a result of the multigenic nature of yield and genotype × environment interactions in the broad geographical range of hard red spring wheat in the Prairies (McCaig and DePauw 1995).

Some of the main characteristics of the growing seasons in Western Canada include: low temperature at the start and at the end of the growing seasons, short growing seasons (95-125d) as well as long days (>14h). Because of these conditions, the breeding goals have been to develop early maturity cultivars which are not exposed to the frost damage in the cold seasons (Iqbal et al. 2006).

Western Canada has nine different classes which account for more than 95% of Canadian wheat. The cultivars released from breeding programs are expected to meet the agronomic performance, resistance to biotic parameters and end use quality types needed for both domestic and export markets (DePauw et al. 2011).

1.2.3. Canada Western Red Spring Wheat (CWRS)

CWRS cultivars have a wide area of adaptation and flour milling properties which enables production of many bakery goods under different manufacturing conditions. The price of this class of wheat is high in world markets. The wheat area in the three prairie provinces is mainly allocated for the production of CWRS, averaging 8.8 M ha between 1941 and 2007 (McCallum and DePauw 2008).

The first cultivar brought to western Canada was Red Fife in about 1870 (Dickenson 1976). Wheat production area increased rapidly in Manitoba during 1900-1905 due to the excellent end use quality of Red Fife. However, this cultivar had several problems, including late maturity which results in frost damage, susceptibility to lodging and stem rust and also a tendency to shatter (Newman 1928). Red Fife was the predominant wheat cultivar in western Canada before it was replaced by Marquis (McCallum and DePauw 2008).

Marquis is a wheat cultivar which originated from a cross between Hard Red Calcutta and Red Fife in 1892 by Dr. Saunders (Morrison 1960), but it was officially introduced in 1911. The main characteristics of Marquis are its early maturity, shorter stature and higher yields versus Red Fife, while showing similar bread making quality to Red Fife (Morrison 1960), and lower shattering than Red Fife (Newman 1928). Marquis was the predominant cultivar in Canada before 1939, before being replaced by Thatcher (McCallum and DePauw 2008). In 1928, 59% of the rail car shipments were downgraded because of frost damage in Marquis (Geddes et al. 1932).

The cultivar Garnet which was released in 1926 was earlier maturing than Marquis and had more resistance to frost, especially in the northern region of Alberta and Saskatchewan. Garnet, a popular cultivar for producers, demonstrated a lower end use quality than Marquis. The Associate Committee on Grain Research approved end use quality testing based on Marquis quality as the reference (Irvine 1983).

Severe epidemics of stem rust occurred in western Canada in 1902-1904, 1916, 1923, 1927-1928, 1935, 1937 and 1938 (Craigie 1944). Leaf rust which was less damaging that stem rust occurred in many of these years, including 1921, 1925, 1927, 1930, 1932 and 1935 (Craigie 1939).

Due to the susceptibility of Marquis to stem rust and the consequent yield losses during epidemic years, Thatcher, a stem rust resistant cultivar, eventually replaced Marquis (McCallum and DePauw 2008). Thatcher was developed at the University of Minnesota and was released in Canada in 1935 (Hayes et al. 1936). Thatcher had the high end-use quality of Marquis in addition to genetically complex stem rust resistance (Knott 2000). This cultivar was resistant to other diseases such as Fusarium head blight (FHB), common bunt (*Tilletia tritici*) and had early maturity and high lodging resistance and high grain yield (Hayes et al. 1936). During 1939-1968, Thather was the predominant wheat cultivar in western Canada from 1939 until 1951. Thatcher and some other stem rust resistant cultivars were produced in the eastern prairie regions of Manitoba and Saskatchwan where stem rust was a frequent wheat disease (McCallum and DePauw 2008).

During 1952-1955, there was a significant increase in the incidence of stem rust due to race 15B-1 that attacked and broke down resistant cultivars (Peturson 1958). This stem rust epidemic was accompanied by leaf rust epidemics, to which Thatcher was highly susceptible and led to significant yield losses (McCallum and DePauw 2008). In 1953, breeding efforts led to the development of a stem and leaf rust resistant cultivar, Selkirik (Martens and Dyck 1989). This new cultivar was resistant to wheat stem rust race 15B-1 and also had better leaf rust resistance (McCallum and DePauw 2008). Selkirk had a higher yield than Thatcher during the time of epidemics of stem and leaf rust (Peturson 1958). However, Thatcher yielded more grain than Selkirk when these diseases were not epidemic; meaning that Selkrik was only a suitable cultivar for the period of epidemic rust diseases and its yield and grain quality were much lower than Thatcher and Marquis, respectively (Irvine 1983). Because of the high grain yield, and excellent wheat end-use quality, Thatcher was suitable as a cultivar and also as a future parent of CWRS (McCallum and DePauw 2008).

Manitou was released in 1965 and remained the predominant cultivar from 1968-1972 and replaced both Thatcher in the west and Selkirk in the eastern parts of the prairies (McCallum and DePauw 2008). Neepawa which was registered in 1969, became the predominant cultivar in

1973 when it replaced Manitou. It had an improved bread-making quality and rust resistance, earlier maturing, more lodging resistant and higher yielding than Manitou (Campbell 1970). Neepawa had good leaf rust resistance due to the presence of *Lr13* and stem rust resistance genes from Thatcher (Campbell 1970). It rapidly spread throughout western Canada and remained the predominant wheat cultivar in all three prairie provinces.

Neepawa was replaced by Katepwa in 1986 due to its good bread-making quality, better stem and leaf rust resistance and easier threshability while still retaining resistance to shattering (Campbell and Czarnecki 1987).

Columbus, registered in 1980, was also among the popular cultivars during the 1980s and 1990s (McCallum and DePauw 2008). The main characteristic of Columbus was its high resistance to pre-harvest sprouting (Campbell and Czarnecki 1981) because of low levels of alpha amylase activity and a long dormancy (Dyck et al. 1986). Columbus had a better leaf rust resistance than Neepawa because of *Lr13* and *Lr16* coming from line RL4137 (Martens and Dyck 1989). Due to its late maturity, tall stature, and moderate susceptibility to seed shelling after maturity, the production of Columbus was limited (McCallum and DePauw 2008).

A cultivar showing both a high grain yield and a high protein concentration was Laura which was registered in 1986 (DePauw et al. 2007). It was the first major CWRS which had *Lr34* for leaf rust resistance, the most effective and durable rust resistance gene in Canada (McCallum et al. 2007a and b) and across the world (Singh and Huerta-Espino 2003). Also, *Lr34* is linked with the stripe rust resistance gene *Yr18* (Suenaga et al. 2003). Laura also has shown a good resistance to powdery mildew (Spielmeyer et al. 2005). Laura never became a predominant cultivar because of its medium late maturity, moderate straw strength and moderate susceptibility to seed shelling (McCallum and DePauw 2008). Katepwa remained the predominant CWRS cultivar on the prairies until 1995 (McCallum and DePauw 2008).

CDC Teal not only had early maturity (Hughes and Hucl 1993) but also showed good resistance to leaf rust due to *Lr1*, *Lr13* and *Lr34* (Liu and Kolmer 1997a) and stem rust. AC Barrie, registered in 1993, became the predominant cultivar from 1998-2005. It was higher yielding, shorter, less prone to lodging, and had higher protein content than the previous leading cultivars such as Katepwa and Neepawa (McCaig et al. 1996).

More recent cultivars such as McKenzie, registered in 1997, showed 19.4% higher yielding than Neepawa (Graf et al. 2003) and had a high resistance to leaf rust (DePauw et al. 2011). Superb which was registered in 2001 became the leading CWRS cultivar in 2006. It was 24% higher yielding than Neepawa and slightly higher grain yield than McKenzie (Townley et al. 2010).

Lillian, registered in 2003 is the first solid stem cultivar (filled with pith, especially in the lower parts of the plant) which has comparable grain yield to hollow stemmed CWRS cultivars. It had medium early maturity and due to the presence of the gene *Gpc-B1*, it had a high protein content (DePauw et al. 2005). As well as these characteristics, it also contains *Yr18*/*Lr34* and *Yr36* and became the main CWRS cultivar in 2007.

Table 1-2 presents some information about the recent cultivars in the western Canada including, the registry year, breeding institution and the primary traits. The most popular cultivars of CWRS grown in 2010 were: Lillian, Harvest, Superb, CDC Go, AC Barrie and McKenzie.

Over a 90 year period of CWRS cultivar development in western Canada, it was found that the yield potential showed an average increase of 6.9 Kg ha^{-1} yr^{-1} (McCaig and DePauw

1995). More available resources beside improved breeding methods led to an increase in the rate of genetic gain (0.74% per year) in the period of 1975 until 2003 (DePauw et al. 2007). While only six CWRS cultivars were registered during 1975 to 1985, 17 and 30 cultivars were registered from 1986-1996 and from 1997-2007 respectively. New cultivars show a greater range in traits than in past years and as these days there are many improved wheat cultivars available, different CWRS cultivars can be grown in the prairie provinces in the future (McCallum and DePauw 2008).

1.2.4. Breeding of Amber Durum wheat in western Canada

Durum wheat (T. turgidum L. ssp. durum (Desf.) Husn.), was introduced to Canada in the early days of wheat cultivation in this country. During years of epidemics of stem rust (1902 to 1904, 1916, 1923, 1927, 1928, 1935, 1937 and 1938), where most of the hexaploid wheat were susceptible, durum wheat was grown in the rust-prone areas of southern Manitoba and eastern Saskatchewan (Knott 1995). In 1950s, another major epidemic of stem rust race 15B-1 occurred which led to a significant change in the production of durum wheat, which was susceptible to this race (Peturson 1958). Following these epidemics, durum production moved to areas with less of a stem rust problem (western Saskatchewan and southern Alberta (Knott 1995).

Ramsay was the first durum wheat with a high resistance to stem rust race 15B-1 (Knott 1995). Stewart 63, released in 1963 was the first durum wheat that was widely grown in Canada and was the leading durum wheat cultivar in 1967. Stewart 63 was resistant to the stem rust race 15B-1 (Knott 1964). During the 1960s and by 1970, Stewart 63 and Ramsey were both cultivated widely in 68% and 13% of the durum area, respectively.

Hercules (registered in 1969) became the leading cultivar during 1972-1973 and was earlier maturing, more resistant to lodging and had improved end-use quality compared with

Stewart 63 (Leisle 1970). Hercules became the end use quality standard reference for Canadian durum cultivars in 1972 (Irvine 1983).

Wascana (registered in 1971) and Wakooma (registered in 1973) were the predominant cultivars from 1974-1987 where 70% of the seeded area belonged to these two. These both were higher yielding than Hercules, with similar end-use quality and disease resistance to Hercules (Hurd et al. 1973). Wakooma, which has stronger gluten than Wascana, was preferred in the export market (Hurd et al. 1973). However, Wascana exhibited higher yellow pigment content and the blend of these two cultivars was in high demand in the Italian market (McCallum and DePauw 2008).

Kyle (registered in 1984) was the predominant cultivar during 1988-2004. It had 5% more grain yield than Wascana and Wakooma, while retaining good end-use quality and disease resistance (Townley-Smith et al. 1987). Kyle replaced for AC Avonlea (registered in 1997) in 2005 due to its higher yield and its shorter and stronger straw. However, both had similar maturity and disease resistance (Clarke et al. 1998).

AC Strongfield was the leading durum wheat cultivar in 2007. It had a reduced tendency to absorb cadmium in addition to significantly higher grain yield and shorter and stronger straw than Kyle (Clarke et al. 2005). Its protein content, yellow pigment amount and gluten index were higher than Kyle (McCallum and DePauw 2008).

In the late 1980s, the Canadian Wheat Board was looking for cultivars with stronger gluten than the conventional CWAD wheat which this led to the introduction of AC Navigator (registered in 2002). AC Navigator, as the first semidwarf CWAD cultivar, also had a higher yellow pigment content than the checks (McCallum and DePauw 2008). While having similar kernels to the CWAD standards, AC Navigator had different end-use quality (McCallum and DePauw 2008).

AC Commander (registered in 2004) is an extra strong CWAD cultivar which had 5% more yield a higher yellow pigment content and a higher gluten index than AC Navigator (McCallum and DePauw 2008). Recent cultivars of durum wheat showed a higher yield and end-use quality, while being shorter statured than the older durum wheat cultivars (McCaig and Clarke 1995).

1.2.5. Canada Prairie Spring Wheat Red (CPSR)

A new wheat class, called Canada Prairie Spring (CPS) was established in 1985 (DePauw et al. 1987). This class with medium protein content, medium mixing strength and medium kernel hardness was referred to as ‘3M’’ (Hetland 1978). CPS cultivars were distinguishable from the CWRS cultivars by their kernel size and shape (McCallum and DePauw 2008). Due to the high grain yield potential and the option for delivery into human food or animal feed, CPS-red became the third largest class (McCallum and DePauw 2008). This class became very popular in Alberta due to the high demand for feed wheat.

AC Taber contained the gene *Bt10* which is a bunt resistant gene (Knox et al. 1992). Also, it had improved leaf rust resistance due to the presence of genes *Lr14a*, *Lr13* and *LrTb* (Liu and Kolmer 1997b). AC Taber gluten quality was better than in the previous CPSR cultivars (McCallum and DePauw 2008).

AC Foremost, which was registered in 1995, was also a popular CPS red cultivar during 1998-2006. It was earlier maturing than AC Taber and also was resistant to loose smut (Knox et al. 1999) as well as common bunt (Thomas et al. 1997) and had improved pre-harvest sprouting resistance. AC Crystal, registered in 1996, was the predominant cultivar during 2000-2005. It was more resistant to loose smut than AC Taber and had higher gluten strength (McCallum and DePauw 2008). The leading CPS cultivar during 2006-2007, 5700PR, was the first CPS cultivar with complete resistance to leaf rust and had 4.3% higher yield than AC Crystal (McCallum and DePauw 2008).

1.2.6. Canada Western Extra Strong (CWES)

After the Second World War, the motivation of western Europe to be self-sufficient in wheat production and also changes in their baking industry led to a drastic decrease in CWRS importation (McCallum and DePauw 2008). Following annual meetings of the members of the Canada Committee on Grain Breeding during the late 1960s and early 1970s, Canadian farmers were requested to grow the high-yielding semi-dwarf spring wheat cultivars (introduced by the International Maize and Wheat Improvement Centre (CIMMYT) program, based in Mexico) instead of CWRS cultivars (McCallum and DePauw 2008).

The introduced semi-dwarf cultivars by CIMMYT had different bread making qualities from the Marquis-based CWRS wheat. Pitic 62, registered in 1969, was the first of these high-yielding semi dwarf cultivar. It had 30% more yield than Manitou under irrigated conditions; however, it had 20% lower protein content (Dubetz 1972). It had also 10% more yield than Neepawa in long-term dry-land trials (DePauw et al. 1986) and weak gluten properties (McCallum and DePauw 2008). Due to its high yielding and low end-use quality, Canada Utility (CU) which was a new market class was introduced in 1972 (McCallum and DePauw 2008).

After Pictic 62, Glenlea (registered in 1972), was the next major CWES wheat cultivar. It had different bread-making qualities from Marquis. While Glenlea was a high yielding cultivar (24% more than Neepawa), it had high gluten strength and harder kernels than Pitic 62 (Evans et al. 1972). Glenlea had good resistance to stem and leaf rusts and loose smut and was planted extensively in Manitoba and eastern Saskatchewan which were prone to rust (McCallum and DePauw 2008). Glenlea became an ideal wheat for frozen products because of its strong gluten which made it tolerant to the freezing and thawing cycles (McCallum and DePauw 2008). In 1993, the Canada Utility class's name was changed to the Canada Western Extra Strong (CWES) in order to promote this type of wheat products (DePauw 1995). Glenlea was the most popular cultivar within the CWES class during the period from 1994 to 1997 where it was grown on 86-98% of the CWES area in Manitoba. It was the predominant CWES cultivar during 1998-2002 and from 2005-2006.

CDC Rama which was registered in 2001 was the predominant CWES cultivar in 2007. The area seeded to CWES cultivars was reducing during 2001-2007 due to reduced international demand. This was a result of technological changes in North America which decreased the demand for CWES gluten to make frozen dough products and also the release of cultivars with strong gluten content in other countries (McCallum and DePauw 2008).

1.2.7. Canada Prairie Spring Wheat White (CPSW)

The first cultivar in the CPSW class was the white-seeded cultivar Genesis (HY355), registered in 1988 and grown widely in 1991 (McCallum and DePauw 2008).

AC Karma, registered in 1994, became the leading cultivar from 1998-2002. It was earlier maturing than Genesis and had much greater milling properties compared the Neepawa. It had a high resistance to stem and leaf rust, loose smut and common bunt (Knox et al. 1995).

AC Vista (registered in 1996), which had improved pre-harvest sprouting resistance and better end-use quality compared with AC Karma, was the predominant CPS-white cultivar during 2003-2007 (DePauw et al. 1998).

Due to the new high-yielding CWRS cultivars such as McKenzie and Superb, production of CPS cultivars declined and currently high yielding CPS cultivars are used only for feed stock and the production of ethanol (McCallum and DePauw 2008).

1.2.8. Canada Western Soft White Spring (CWSWS)

Canada Western Soft White Spring (CWSWS) was grown exclusively in southern Alberta under irrigated conditions (Beres et al. 2008). The CWSWS cultivar was a preferential choice for producers of confectionary and cracker products because of the low protein concentration and weak gluten strength. The area under cultivation of this class has always been smaller than the other wheat classes in western Canada (McCallum and DePauw 2008). Kenhi was the first cultivar (registered in 1958) in this class and had been produced at the University of Alberta (Dickinson 1976).

The US-bred high-yielding semi-dwarf cultivar Fielder (registered in 1976) was the leading cultivar from the late 1970s until 1996 (DePauw et al. 1986).

AC Reed (registered in 1991) had a higher yield than Fielder while showing similar milling quality (Sadasivaiah et al. 1993). This cultivar was resistant to stripe rust, the problematic disease in south west Alberta. AC Reed remained the leading cultivar until 2003 before its replacement by AC Andrew (registered in 2001). AC Andrew was higher yielding than AC Reed while having a better bunt resistance (Sadasivaiah et al. 2004).

AC Bhishaj (registered in 2003) had higher yield than AC Reed (9%) and was similar to AC Andrew. However, AC Bhishaj had weaker straw than both (Randhawa et al. 2011).

In recent years in the area under irrigated conditions, the cultivars from CWAD and CWRS have been grown more extensively since they have high lodging resistance, are strong strawed and garner a higher average price compared with the CWSWS class. The current interest in CWSWS cultivars is mainly for the production of ethanol, due to the high yield potential of this class (McCallum and DePauw 2008).

1.2.9. Canada Western Hard White Spring (CWHWS)

Most of the high end-use quality wheat grown in the rest of the world is hard white wheat. In order to produce cultivars with similar end use quality to that of CWRS for meeting the Asian market opportunities (for noodles and pan breads), the Canadian wheat board (CWB) encouraged the breeding and release of hard white cultivars (McCallum and DePauw 2008). Therefore, the Canada Western Hard White (CWHW) class was introduced in 2001 with the registration of Snowbird (Humphreys et al. 2007).

During 2003-2007, 98.1% of the seeded area of CWHWS was allocated to Snowbird (McCallum and DePauw 2008). Snowbird bread-making quality is very similar to the CWRS class while having a white seed coat and pre-harvest dormancy. The future of this class depends very much on the demand for the hard white wheat grain as well as its acceptance by the prairie producers (McCallum and DePauw 2008).

1.3. Agronomic traits in western Canadian wheat cultivars

Due to different challenges, including economic returns on wheat production, lodging, frost damage, disease, and insect problems, many important traits have been added to western Canadian wheat cultivars in order to overcome these challenges. These agronomic traits in cultivars include yield increase, end-use quality, early maturity and disease resistance (McCallum and DePauw 2008), which are explained in the following section.

1.3.1. Yield increase

Yield depends on different factors such as weather, crop management and genetic changes (McCaig and DePauw 1995). Yearly precipitation has an important effect on yield. Environmental variation influences grain yield more than genetic variation within wheat classes (Wang et al. 2002).

Grain yield is a function of yield components of mean kernel weight and kernel number per unit area. Kernel number itself is the function of spikes per plant and kernels per spike. The results show that increased yields of new cultivars are more strongly associated with the increased number of kernels per spike, rather than an increased number of spikes per plant (Wang et al. 2002; McCaig and DePauw 1995). Moreover, Sticksel et al. (2000) reported that nitrogen fertilization aimed at increasing the sink capacity per spike was an important tool to maximize wheat yields.

1.3.2. Protein concentration

Protein content is an important trait due to its important effect on processing quality. Environment had been found to be the most influential component of protein content (Finlay et al. 2007). Environmental conditions such as timing, precipitation, moisture distribution, temperature, soil nitrogen level, influence the yield and protein content significantly (Petrosini and Leone 1948, Rennie 1956). Under normal moisture conditions, yield is high and protein content is normally lower than average. However, in hot, dry conditions yield is lower and protein content increases due to lower starch accumulation (Cutforth et al. 1990).

Cultivars in the CWRS class show the highest protein content among western Canada wheat classes which is an essential requirement of this class for registration (Pswarayi et al. 2014). The high protein content of CWRS class makes it suitable for blending and for making high volume pan bread. Recent CWRS cultivars show high yields beside their high protein content which, was not the case for earlier registered cultivars in this class (Pswarayi et al. 2014). CPS class cultivars have the advantage of higher yield than CWRS class cultivars, however, they exhibit much lower protein content (Wang et al. 2002).

Advances in end-use quality in prairie wheat cultivars include increased protein content, increased milling yield, better gluten strength, improved bread-making quality, and reduced susceptibility to pre-harvest sprouting (McCaig and DePauw 1995). Due to breeding efforts, good end use quality CWRS cultivars such as Lillian and Somerset (registered in 2005) and the CWES cultivar Burnside (registered in 2004) have high protein content, as the result of the high protein content gene *Gpc-B1* (McCallum and DePauw 2008).

1.3.3. Early maturity

Early maturity is a key consideration of spring wheat breeding programs in northern growing regions of western Canada due to the short growing seasons (95-125 d), low temperatures in the beginning and at the end of the growing season, and long days (>14 h) in order to avoid frost damage which lowers the production and quality (Iqbal et al. 2006). Early-maturing cultivars, such as AC Splendor (registered in 1996) are very suitable for these regions. Another important advantage of the early maturing cultivars is their resistance to pre-harvest sprouting in the cold and wet harvest conditions (Hucl and Matus-Cadiz 2002).

1.3.4. Disease resistance

Improvement in disease resistance has been one of the major achievements of wheat breeding efforts in western Canada. Stem rust caused by *Puccinia graminis tritici* is one of the most destructive wheat diseases in the prairies, which with the development of the resistant CWRS cultivars through breeding, the problems have been largely controlled. Thatcher which contains stem rust resistance genes such as *Sr6*, *Sr7a*, *Sr9b*, *Sr11* is an example of this kind (McCallum and DePauw 2008).

Leaf rust caused by *Puccinia triticina* is the second most important disease in western Canada. Leaf rust resistance genes such as *Lr1*, *Lr10*, *Lr13*, *Lr14a*, *Lr16*, *Lr21*, *Lr22a* and *Lr34* provide important protection (McCallum et al. 2007a). These genes are present in some leaf rust resistant cultivars such as McKenzie, Lovitt, CDC Alsask, 5500HR and 5600HR (Hiebert et al. 2007).

Common bunt is another destructive disease which was improved by addition of *Bt10* into cultivars such as AC Cadillac, AC Karma and AC Taber (Gaudet et al. 1993).

Stripe rust has always been a concern in southwest Alberta, Manitoba and Saskatchewan (McCallum et al. 2007b). Resistance genes have been added to some of the CWSWS cultivars, such as AC Reed (Sadasivaiah et al. 1993). The major adult resistance gene *Lr34*/*Yr18* has been an important gene introduced into the CRWS class for controlling both stripe and leaf rust.

1.4. Wheat diseases in western Canada

1.4.1. Stem rust

Stem rust or black rust of wheat is the most destructive type among the rusts and is caused by the fungus *Puccinia graminis f.sp. tritici.* Stem rust is a heteroecious fungus which needs two hosts to complete its life cycle. The primary hosts for *P. graminis f.sp. tritici* are wheat, barley, and triticale. The main alternate host of *P. graminis* is common barberry (*Berberis vulgaris*) on which the fungus over-winters and goes through sexual reproduction.

The stem rust fungus infects in warmer temperatures than leaf rust. The optimum conditions for stem rust infection are 8 to 12 hours of dew at 18 °C, available free water and

10,000+lux of light. When temperature rises to 30 °C and dew slowly dries, infection occurs (Rowell, 1984).

P. graminis is a macrocyclic fungus producing five kinds of spores during its life cycle, which are the urediniospore, teliospore, basidiospore (on primary host), pycnidiospore, and aeciospore (on alternate host). Stem rust uredinia occur on the stem, leaf surfaces and also on leaf sheaths, spikes, glumes, awns and even on grain. Urediniospores are wind-dispersed, have a rapid growth cycle (8 days), and produce many spores. Each pustule of stem rust can produce 10,000 urediniospores per day (Manners 1960). Urediniospores are transferred by wind for long distances (upwards of 800 km) across the North America Great Plains every year (Roelfs 1985) and 2000 km from Australia to New Zealand (Luig 1985). However, it has been transferred for about 8000 km from East Africa to Australia only three times during the past 75 years (Watson and Sousa 1983).

Stem rust has a significant impact on wheat as it lowers yield and causes severe lodging,which can occur in an apparently healthy crop three weeks before harvesting. For controlling stem rust in the North America and Europe, several approaches have been used. The first approach is eradicating the alternative host which reduces the amount of inoculum and the number of combinations of virulence. The second approach is planting early maturing cultivars which reduces the extent of damage and prohibits severe rust infections. This occurs because in the early growing season the inoculum density is lower. Finally the most important controlling method is genetic control which will be explained in the next section.

1.4.1.1. Stem rust in Canada

Stem rust has been an annual threat to cereals growers since the early cultivation of cereals in Canada. In 1916, 1927, and 1935 stem rust epidemics caused devastating losses. Most cereal fungi overwinter in the southern United States while in the spring, urediniospores are carried by wind towards the north, midwestern and northern States (Roelfs 1985).

The primary method for controlling stem rust in Canada is genetic host resistance. After the severe stem rust epidemic of 1916, cereal breeding for rust resistance was initiated. The Dominion Rust Laboratory in Winnipeg was established in 1925 for this purpose (Goulden and Stevenson 1949).

Red Fife was the dominant cultivar during 1870-1909. It had an excellent end-use quality, but late maturity. It was then replaced by Marquis during 1910-1938 having early maturity and higher yielding than Red Fife. However, both of these genotypes were susceptible to stem rust and when the major epidemics happened at that time substantial yield losses occurred. Thatcher, the first stem rust resistant cultivar, was released in 1939. It was the most popular wheat cultivar in western Canada during 1939-1967 being grown on over 50% of the seeded areas. Thatcher had similar end-use quality like Marquis, while genetically it was modified to be resistant against stem rust. Thatcher has *Sr9g*, *Sr5*, *Sr12*, and *Sr16* in addition to some unidentified genes for high levels of stem rust resistance (Knott 2000).

Other stem rust resistant cultivars, Regent, Renown, and Apex, were grown for many years in the eastern prairie region of Manitoba and eastern Saskatchewan where stem rust was a major problem. In 1953-1955 epidemics happened which were caused by race 15B which could attack these cultivars (Peturson 1958). Breeding efforts to develop stem rust resistance led to the release of Selkirk that carried *Sr2*, *6*, *7b*, *9d*, *17*, and *23* (Kolmer et al. 1991). After the release of Selkirk, commercial wheat fields have been largely free of stem rust. Selkirk replaced Thatcher in the eastern prairie where stem rusts is severe. The presence of alien resistance genes such as *Sr2* (from *Triticum turgidum*) along with *Sr24*, *Sr26*, *Sr31*, *Sr36*, or *Sr38* from wild relatives of wheat led to increased rust resistance in many countries for over three decades (Singh et al. 2008).

Eradication of barberry (an alternative host) in the United States and Canada had a large impact on controlling stem rust since it eliminated the sexual cycle and decreased the number of new races (Roelfs 1985). All CWRS cultivars are now resistant to stem rust, but the gene combinations that are responsible for this resistance are unknown in these cultivars.

Because of the durability of stem rust resistance in Canadian wheat, all these cultivars have existed for more than 50 years but still their diverse resistance needs to be improved. If a new race is introduced in Canada, it would have the potential to cause a major rust epidemic, because it has virulence against many *Sr* genes and also too many Canadian wheat cultivars (Fetch and Jin 2005). Ug99 was found in Kenya in 2006 and 2007 affecting about 90 % of the world's wheat cultivars (Singh et al. 2008) including most Canadian wheat cultivars (Fetch 2007). Stem rust resistance genes such as *Sr6*, *7a*, *7b*, *9a*, *9b*, *10*, *11*, *12*, *16*, *17*, and *Wld-1*, present in the North American wheat cultivars were found to be ineffective against this race (Jin and Singh 2006). Lillian from CWRS class, which was the most grown wheat in western Canada, is susceptible to Ug99 (DePauw et al. 2009), and all of the popular spring wheat cultivars are susceptible (Ghazvini et al. 2012). Host resistance has been the main tool for controlling stem rust for over 50 years. In order to improve the resistance to new exotic races such as Ug99 in modern wheat cultivars, it is necessary to incorporate a stack of resistance genes in them (Ghazvini et al. 2012).

1.4.2. Leaf rust

Leaf rust is a fungal disease that is caused by *Puccinia triticina*. It is a worldwide disease and is found wherever wheat grows. However, the center of its origin is in the Fertile Crescent region of the Middle East. It is the most common rust disease observed which causes yield loss (from trace to 30% or even more).

Leaf rust is a macrocyclic fungus and produces five kinds of spores: uredospore, teliospore, basidiospore (on primary host), pycnidiospore, and aeciospore (on alternate host). It is a heteroecious fungus with two unrelated hosts. Primary hosts of the pathogen are hexaploid wheat (*T. aestivum* L.) as well as durum wheat, wild emmer, domesticated emmer and triticale (Roelf et al. 1992). The alternative hosts where sexual reproduction occurs are *Thalictrum* spp. in the North America, *Thalictrum speciosissimum* in Southern Europe (Casulli 1988), and *Isopyrum fumaroides* in Siberia (Chester 1946).

Maximum leaf rust infection on wheat is favored when spores are available, there are susceptible or moderately susceptible plants, humidity is 100%, temperature is 20 °C, light is low, dew is present for 6-8 hours, there is free water available and nights are cool while days are warm. In favorable conditions, the fungus can germinate and penetrate into the leaf. After 12-24 hours, haustorium are formed and take many nutrients of the leaf cell and tightly sticks to the host cell wall. Severe epidemics and yield losses occur when the flag leaf is infected before anthesis (Chestler 1946). Susceptible cultivars have large uredinia without causing chlorosis or necrosis in the host tissue. However, in resistant cultivars, small to moderately sized of uredinia are formed and surrounded by chlorotic or necrotic zones. The yield loss in susceptible cultivars is approximately 58% whereas in resistant cultivars it ranges between 12 to 28 % (Samborski and Peturson 1960).

1.4.2.1. Leaf rust in Canada

Wheat leaf rust is an annual production problem for Canadian wheat producers. Leaf rust is more severe in the eastern prairies of Manitoba and Saskatchewan and southern Ontario. Bread wheat cultivars that mostly grow in the prairie provinces are susceptible to leaf rust. However, durum wheat cultivars have traditionally been resistant to leaf rust. The CWRS cultivars Marquis and Thatcher, which were predominant cultivars from 1910 to 1939 and 1939 to 1967, respectively are both very susceptible to leaf rust. Resistance gene *Lr14a* is carried in cultivars Renown, Regent, and Redman and after that into stem rust resistant cultivar Selkirk (Martens and Dyck 1989). Selkirk that carries *Lr10*, *Lr14a*, and *Lr16* was the predominant cultivar in the eastern prairies during 1955-1970 (Samborski 1985; Martens and Dyck 1989). Virulence to these genes was developed in the *P. triticina* population and increased to 56% in 1966 (Samborski 1985). Three cultivars Manitou, Neepawa, and Katepwa were predominant during 1967-1993. Theses cultivars carry gene *Lr13* for leaf rust resistance, which provides a moderate level of resistance. The next predominant cultivar was AC Barrie (1994-2005), having the combination of both *Lr13* and *Lr16* (Kolmer 2001). When they were introduced, they showed resistance to the prevalent *P.triticina* population, but when the pathogen population changed, AC Barrie had a high level of leaf rust infection. The peak of virulence to *Lr16* increased to 58.8% in isolates collected in 2001 (McCallum and Seto-Goh 2004).

Another resistance gene that is relatively common in Canadian cultivars is *Lr34* (Kolmer 1996). For many years it provided high resistance to leaf rust. The cultivar Glenlea that carries gene *Lr34*, *Lr1*, and *Lr13* (Dyck et al. 1985) had shown an effective level of resistance for 30 years. Glenlea was grown extensively in eastern prairies of Canada. The success of *Lr34* increased when combined with the other effective resistance genes (German and Kolmer 1992). Cultivars AC Domain, Roblin, Laura, AC Splendor, and CDC Teal *Lr34* were mixed with additional resistance genes. If these additional genes are overcome by the *P. triticina* population, the presence of resistance gene *Lr34* can provide moderate resistance in cultivars.

The strategy for breeding resistance to leaf rust should include combining durable resistance genes in addition to one or more effective genes having high resistance to rust (Dyck and Kerbe 1984).

1.4.3. Stripe rust

Stripe rust, also known as yellow rust, is a cool season disease of cereals and grasses. It is caused by the fungus *Puccinia striiformis* and can affect wheat, barley and triticale, among which wheat is more susceptible. The optimum conditions for stripe rust infection occur when the temperature is between 9-13 ºC, free water is available and light is low. Dispersal of stripe rust is not similar to leaf and stem rusts, due to their susceptibility to ultraviolet light. Spores of stripe rust cannot transfer for long distances because of this sensitivity. Stripe rust can be spread by humans for long distances (Maddison and Manners 1972). The wheat stripe rust pathogen is mainly microcylic, although *Berberis chinensis* was recently identified as alternate host (Jin et al. 2010).

The pathogen infects the green tissue of cereals and grasses and can infect the plant at any stage from the appearance of the first leaf to near maturity. One week after infection, the symptoms appear and sporulation starts after 2 weeks under favorable conditions (7-20 °C). The infection is characterized by yellow-orange pustules that form in parallel lines on the leaf surface which can be easily distinguished from the oval, darker-colored rust pustules of leaf rust (Chen 2005).

P. striiformis is most likely a hemiform rust which has only uredinia and telia stages in its life cycle. Epidemics may result from the spread of fungal spores carried on travelers clothing, or when the environmental conditions are favorable, air currents are the main agent responsible for spreading this disease (Roelf et al. 1992). The stem can also be infected, causing similar symptoms.

When the infections develop into the middle or the upper parts of the plant canopy, major yield losses and grain reduction occur due to infection of leaves; since the top three leaves of the wheat plant contribute approximately 70-75% to the photosynthetic yield. Leaves and the green parts of the plant are covered by pustules, so photosynthesis is reduced (Roelf 1985).

Airborne spores spread from the Pacific Northwestern United States are the main cause of strip rust infections (Su et al. 2003). Cold winters in western Canada can kill the fungus and prevent overwintering of the pathogen (Rapilly 1979). Recently, stripe rust has become more problematic in wheat production in western Canada due to milder winters leading to overwintering of the fungus. This causes early infection and increased damage to spring wheat. Stripe rust is now a common disease in southern Alberta. Manitoba and Saskatchewan were the first areas in Canada affected by stripe rust in 2000 (Chen et al. 2002). A serious wide spread epidemic of stripe rust was reported in 2005 near Regina (McCallum et al. 2006). Most western Canadian wheat cultivars were found to be susceptible to stripe rust, many of which had an intermediate level of resistance while a few of them showed a higher resistance. It was thought that the high stripe rust resistance cultivars carried the adult resistant gene *Lr34/Yr18* genes (Fetch 2011). Most of western Canada wheat classes such as Canada Western Red Spring (CWRS) and Canada Prairie Spring Red (CPSR) (Puchalski and Gaudet 2011) are affected by this disease. Durum wheat shows the highest resistance against stripe rust, however, CPSR and CPSW exhibit the least resistance (Radhawa et al. 2012).

1.5. Summary

Wheat is grown on more area than any other crop in the world and, along with rice, is the most important crop for direct human consumption. The increasing human population necessitates wheat improvement. Characterization and understanding of wheat evolution and the genetic diversification of various wheat species and relatives have important roles in wheat quality improvement.

The major goal of wheat breeding has been to increase the grain yield but since the geographical range of planted hard red spring wheat is broad in the Canadian prairies, achieving this goal is difficult. The short growing season of central and northern regions of the prairies limits such areas to early maturing cultivars. Wheat areas of Manitoba and eastern Saskatchewan are prone to severe infestation of rusts. Therefore, due to the aforementioned reasons, Canadian wheat breeding focuses on increasing the wheat quality and disease resistance.

The future target of wheat cultivars on the Canadian prairies is in achieving high yield, good disease resistance, improved end use quality, and good agronomic characteristics. Increasing demand for feed grain and industrial uses such as fermentation of ethanol could become another important factor in wheat cultivar development in Canada.

1.6. Research objectives

Breeding efforts have been important in solving the challenges of wheat production in western Canada. One of the main goals of breeding programs in western Canada has been increasing grain yield while maintaining end-use quality of wheat. Several agronomic traits including test weight, maturity, plant height, lodging resistance and disease resistance have significant effects on grain yield. In order to obtain high yields, it is crucial to optimize these traits. The next challenge of wheat production in western Canada is the short growing season which forces breeders to develop early maturing cultivars. Improving the disease resistance (especially rust) of cultivars has been another major objective for the breeders in western Canada in order to prevent such epidemics.

The major objectives of the current research are as follows:

1. Analyzing the effect of breeding on grain yield and associated traits in western Canadian wheat cultivars.
2. Studying the correlation between grain yield, agronomic traits and protein content in Canadian cultivars.

2. Materials and Methods

In the present study, we examined 100 western Canadian spring wheat cultivars belonging to seven commercial wheat classes, and released over 126 years. The wheat cultivars included 62 Canada Western Red Spring (CWRS), 14 Canada Western Amber durum (CWAD), 9 Canada Prairie Spring (CPS), 6 Canada Western Extra-Strong (CWES), 4 Canada Western Soft White Spring (CWSWS), 3 Canada Western General Purpose (CWGP) and 2 Canada Western Hard White Spring (CWHWS) cultivars. Table 2-1 presents the different cultivars grown, their class, year of release and their origins. Red Fife from CWRS class is the oldest cultivar grown (1885, Poland) while the most recent one is PT580 from the same class (2011, Saskatchewan).

These cultivars were grown in seven environments in the Canadian prairies during 2011 to 2013. The experiment was planted on conventional land in Edmonton, Alberta during 2011 and 2012, both conventional and organic land in Edmonton during 2013; conventional land in Kernen, Saskatchewan during 2011 and 2012, and conventional land in St. Albert, Alberta during 2013). The Edmonton's trials were conducted at the Edmonton Research Station (ERS), Edmonton, Alberta (53.5333° N, 113.5000° W). The Kernen (Saskatchewan) and St. Albert (Alberta) locations are at (52.1500º N, 106.5500º W) and (53.6303° N, 113.6258° W). Soils at Edmonton, St. Albert and Kernen were Orthic Black Chernozems (Typic Haplustolls) (Alberta Agriculture Food and Rural Development, 2011).

All trials were designed as randomized incomplete blocks with two blocks in 2011 and three blocks in 2012 and 2013. Each plot was seeded into cultivated soil at a depth of 4-7 cm using minimum disturbance double disk press drills (Fabro Enterprises Ltd., Swift Current, SK). The seeding rate of plots was 300 seeds m^2. Different plot sizes were used in the fields during this period such as Edmonton (4.5 m^2, 5 seeded rows in 2011; 4.25 m^2, 6 seeded rows 2012; and

4.25 m^2 2013), Kernen (4.25 m^2, 5 seeded rows) and St. Albert (4.32 m^2, 5 seeded rows 2013). The trials were not irrigated and were planted in early to mid-May and harvested in mid- to late September. Fertilizers were used at a rate of 90.7 Kg ha^{-1} product of 25-10-10-5 in Edmonton, St. Albert (2011-2013), and Kernen (29.5 Kg ha^{-1} product of 28-23-0-0 ESN). In the 2013 organic trial in Edmonton, the field did not receive any chemical fertilizers and herbicides, and was managed according to the Organic Crop Improvement Association International Certification Standards (Organic Crop Improvement Association 2000).

In this research, the yellow rust resistance status of the 100 western Canadian spring wheat cultivars at Lethbridge (Alberta) and Creston (British Columbia) were studied during 2012-2013. Leaf rust resistance of these cultivars was also studied at Edmonton (Alberta) during this period. Inoculated nurseries were grown with 1 m row plots of each cultivar interspersed every 4 rows with susceptible spreader rows. The screening of genotypes to study rust resistance in the field was carried out using a 1-9 scores, 1 week before harvesting. Scoring of leaf rust and stripe rust was performed using McNeal et al. (1971) scale which is based on the infection of flag leaves and upper leaves, even with other affected tissues. On that scale, immune, very resistant, resistant, moderately resistant, moderately susceptible and susceptible are scored as (0), (1-2), (2-4), (5-6), (7-8) and (9) respectively.

2.1. Data Collection

Days to heading were recorded as the number of days from seeding to when 75% of the emerged spikes in the plot had visible peduncles. After stem elongation was complete, plant height (representing the distance from the soil surface to the tip of the spike, excluding awns in awned cultivars) was recorded on a per plot basis. Days to maturity were recorded as the number of days from seeding to when 75% of the spikes and peduncles in the plot lost their green color

Lodging was scored on a scale of 1 to 9, with 1 representing no lodging (crop standing at 90°) and 9 representing a completely flattened plot. Plots were harvested using a Wintersteiger plot combine at harvest maturity. Grain yield was recorded on a dry weight basis. Yield components (grain yield, test weight, thousand kernel weight) were recorded after cleaning the grain using 2-mm mesh sieves and a grain blower. Total yield (Kg ha^{-1}), test weight (Kg hL^{-1}), and thousand kernel weight (g) were determined for each cultivar. Grain protein content (%) was measured using Near-infrared Reflectance (NIR) spectroscopy by SpectraStar RTW system (version 3.8.0, Unity Scientific, Connecticut, USA).

2.2. Data analysis

Data were analyzed using the GLM procedure in SAS software (version 9.3, SAS Institute Inc., 2013). The following model statement was used:

Trait = Env Rep (Env) Block (Rep*Env) Entry (Entry*Env)

Where, Env = Environment; Rep = Replication; Rep (Env) = Replication nested within environment; Block (Rep*Env)= Block nested within replication and environment (This effect was included in model as all Blocks were incomplete).

For testing different effects against proper error terms, the Test statement was used. The effect of Environment was tested against Rep (Env) as an error term; Entry was tested using Entry*Env as an error term; Entry*Env interaction was tested against the residual error. Analysis within wheat class was conducted by specifying "By Class". In other words, the analysis was conducted as a mixed model, where Environment, Replication and Block were considered random, while cultivar was considered fixed. Least squares means for all traits were estimated in the GLM procedure. Due to non-replicated data, stripe and leaf rusts data were analyzed treating environment as replication in Proc GLM. Associations among the different traits were determined using “Proc Corr” in SAS. The change in different traits over a period of time was determined for the CWRS, CWAD and CPS classes by regressing the mean values of traits over the year of release of the respective cultivars.

3. Results

Temperature and precipitation data during each growing season for each year and location are presented in Tables 3-1 and 3-2. Annual mean temperatures of the three locations during 2011-2013 were relatively similar (Table 3-1) and the optimum temperature for the crop growing season (12-25ºC) was satisfied. The precipitation during the growing seasons was suitable, but not ideal for wheat growth (200-300 mm). The highest level of precipitation was also observed in 2013 (Table 3-2).

3.1. Contribution of various effects to phenotypic variation

3.1.1. Days to heading

Combined ANOVA showed a significant effect ($P<0.001$) of environment, cultivar and cultivar × environment interaction on days to heading (Table 3-3). Among these effects, environment contributed the most towards the phenotypic variation for days to heading (50.8%), followed by cultivar (21.4%) and cultivar x environment interaction 14.5% (Table 3-3).

For Canada Western Red Spring (CWRS), the effects of environment, cultivar and their interactions were significant on days to heading ($P<0.001$) (Table 3-4). Of the total phenotypic variation for days to heading for the CWRS class, 38.5% was due to environment, 35.5% was due to the effect of cultivar, whereas 9.2% was due to environment × cultivar interaction (Table 3-4). Similarly, environment also had the highest effect (41.5%) on phenotypic variation for days to heading of Canada Western Amber Durum (CWAD) class, followed by 24.6% by cultivar and 10.2% by environment x cultivar interaction (Table 3-5).

3.1.2. Plant height

The effects of environment, cultivar and their interactions were found to be significant on the plant height ($P<0.001$). However, the genotypic effect had the highest contribution towards the plant height (28.3%) followed by environment (20.7%) (Table 3-3). For both CWRS and CWAD classes, all the effects of environment, cultivar and their interactions were also significant on plant height ($P<0.01$ for CWRS) (Table 3-4) ($P<0.05$ for CWAD) (Table 3-5).

3.1.3. Days to maturity

ANOVA results indicated that environment was the largest source of variation for time to maturity (54.5%) followed by environment × cultivar (19.5%) and cultivar (17.7%) all showing a highly significant effect ($P<0.001$) (Table 3-3). For the CWRS class, all the effects were significant ($P<0.05$) while the environment effects contributed the most to the variation of days to maturity (59.8%). For the CWAD class, environment, and environment × cultivar effects ($P<0.001$) were both highly significant on days to maturity. In this class, environment (85%) and environment × cultivar interaction (9.4%) were the main sources of variation in days to maturity (Table 3-5).

3.1.4. Lodging

Environment, cultivar and cultivar × environment interaction had highly significant effects ($P<0.001$) on plant lodging, however, unlike the other traits, cultivar (31.6%) showed the most contribution towards lodging. In addition, environment (25.2%) and environment × cultivar (23.9%) caused similar significant effects on lodging (Table 3-3). Similarly, in CWRS and CWAD classes the same phenotypic variations had significant effects on lodging ($P<0.05$) (Table 3-4, 3-5).

3.1.5. Grain yield

A very significant effect of environment, cultivar and their interactions on grain yield was observed ($P<0.001$) (Table 3-3). The overall phenotypic variation for grain yield had 57.2% contribution from environment, 15.4% from cultivar and 11.9% from environment × cultivar interaction (Table 3-3). For CWRS, the effects of environment and environment × cultivar interaction were significant on grain yield ($P<0.001$). For CWAD class, only environment had a highly significant effect on grain yield ($P<0.001$). The phenotypic effect of environment had the most contribution towards the grain yield in both classes (Table 3-4, 3-5).

3.1.6. Test weight (TWT)

The effects of environment, cultivar and their interactions were highly significant ($P<0.001$) on test weight and contributed 44%, 24.5% and 21.5% respectively towards test weight (Table 3-3). Environment effect on test weight was very significant ($P<0.001$) in CWRS and CWAD classes with its contribution being 50.2 % (CWRS) and 65.1% (CWAD) (Table 3-4, 3-5).

3.1.7. Thousand kernel weight (TKW)

Environment, cultivar and their interactions showed a very significant effect on thousand kernel weight ($P<0.001$). Environment (49.6%) had the highest effect on thousand kernel weight followed by cultivar (34.1%). For the CWRS class all of the effects on thousand kernel weight were highly significant ($P<0.001$) with the most contribution from environment (59.5%) followed by cultivar (20.7%) (Table 3-4). For the CWAD class, only environment had a significant effect ($P<0.05$) on thousand kernel weight with a contribution of 79.1% (Table 3-5).

3.1.8. Protein content

ANOVA results showed a highly significant effect (P<0.001) of environment, cultivar and cultivar × environment interaction on protein content (Table 3-3). Environment (46.5%) followed by cultivar (36.7%) showed the highest contribution to variation of protein content (Table 3-3). For the CWRS class, all sources also were highly significant (P<0.001). Of the total phenotypic variation for protein content in CWRS, environment (63.2%) and cultivar (16.3%) had the highest effect on protein content (Table 3-4). For the CWAD class, environmental effects were highly significant (P<0.001) while cultivar and cultivar × environment showed also a significant effect (P<0.05). Environment with 73.7% was the dominant source of variation in protein content (Table 3-5).

3.2. Least squares means of the traits

The least squares means for 8 traits (days to heading, height, days to maturity, lodging, grain yield, test weight, thousand kernel weight and protein content) measured on 100 wheat cultivars in six environments of western Canada are shown in Tables 3-6.

3.2.1. Days to heading

Days to heading varied between 54.4-61.9 days for the 100 wheat cultivars. The CWRS cultivar AC Splendor took the least days (54.4 days) to heading, followed by older CWRS cultivars Park (54.7 days) and Roblin (54.8 days) (Table 3-6). The oldest CWRS cultivar, Red Fife, headed the latest (61.9 days), followed by the Canada Prairie Spring (CPS) cultivars, AC Taber (61.5 days), AC Crystal (61.4 days) and HY682 (61 days) . Within the CWAD class, AC Morse headed the earliest (58.8 days), whereas DT 570 headed the latest (61 days) (Table 3-6).

3.2.2. Plant height

Plant height of the 100 cultivars varied between 80-119 cm. The shortest cultivars were AC Navigator and Commander (80 cm) both from the CWAD class and the tallest were the two old cultivars of the CWRS class, Red Fife and Marquis. The shortest cultivars in the CWRS class were Muchmore (83 cm) and Carberry (85 cm). Within the CWAD class, Kyle (113 cm) was the shortest cultivar (Table 3-6).

3.2.3. Days to maturity

Days to maturity for the 100 cultivars varied between 93.1-106.4 days. The earliest maturing cultivars were CWRS cultivars, AC Splendor (93.1 days), Garnet (94.6 days), AC Intrepid (95.2 days), Roblin (95.8 days) and Infinity (96.2 days). The latest maturing cultivars were also DT570 (106.4 days), Red Fife (106.3 days), Enterprise (105.9 days), CDC Verona (105.9 days) and AC Avonlea (105.4 days) all from CWAD class except for the CWRS cultivar Red Fife (Table 3-6). The latest maturing cultivars in the CWRS class were found to be Red Fife (106.2 days), Carberry (103.8 days), Glenn (103.7 days) and Muchmore (103 days). Within the CWAD class, Commander (102.3 days) and Kyle (102.5 days) matured earliest, while DT570 (106.5 days) and CDC Verona (105.9 days) matured the latest (Table 3-6).

3.2.4. Lodging

The greatest lodging (weakest straw) was observed in the CWRS class and particularly the old cultivars of Garnet, Marquis and Red Fife (Table 3-6).

3.2.5. Grain yield

Yield varied between 3688-6440 Kg ha^{-1}cultivars. The CWSWS cultivars AC Andrew, Sadash, Bhishaj had the highest grain yield (6440, 6298 and 6120 Kg ha^{-1} respectively) among all cultivars (Table 3-6). The CPS cultivars, HY682 (5907 Kg ha^{-1}) and AC Vista (5672 Kg ha^{-1}) were also among the high yield cultivars. The CWRS cultivars, Garnet (3688 Kg ha^{-1}), Marquis (3778 Kg ha^{-1}), Thatcher (3921 Kg ha^{-1}) and Red Fife (3948 Kg ha^{-1}) were the lowest yielding (Table 3-6).

Grain yield in the CWRS cultivars varied between 3670-5326 Kg ha^{-1}. In this class the highest grain yields were observed in CDC Go (5326 Kg ha^{-1}), CDC Stanley (5268 Kg ha^{-1}), BW423 (5163 Kg ha^{-1}), CDC Kernen (5147 Kg ha^{-1}) and Muchmore (5121 Kg ha^{-1}), all released in the last 10 years. Lowest grain yield in this class was found in the old cultivars of Garnet, Marquis, Thatcher and Red Fife (Table 3-6).

The grain yield content of the 14 cultivars in the CWAD class varied between 4231-5464 Kg ha^{-1}. Brigade (5464 Kg ha^{-1}) and CDC Veron (5178 Kg ha^{-1}) yielded the most grain; and Strongfield (4231 Kg ha^{-1}) and Kyle (4283 Kg ha^{-1}) yielded the least in this class (Table 3-6).

3.2.6. Test weight

Test weight of all the cultivars varied from 70.2 to 81.4 (Kg hL^{-1}). The highest test weight was recorded for Glenn (CWRS, 81 Kg hL^{-1}) and CDC Bounty (CWRS, 80.6 Kg hL^{-1}). The lowest test weight was also found in Commander (CWAD, 70.2 Kg hL^{-1}), 5500 HR (CWRS, 74.7 Kg hL^{-1}) and 5702 PR (CPS, 75.3 Kg hL^{-1}) (Table 3-6).

3.2.7. Thousand kernel weight

Thousand kernel weight (TKW) varied between 28.9 and 46.6 g. The highest TKW was found in the few CWES cultivars Glenlea (46.6 gr), CDC Walrus (45.5 gr), CDN Bison (45.2 gr) and CDC Rama (44.4 gr). Garnet (CWRS, 28.9 gr), Snowstar (CWHWS, 30.8 gr), Thatcher (CWRS, 31.6 gr), 5604HRCL (CWRS, 31.7 gr) and Laura (CWRS, 32.1 gr) also showed the lowest TKW values (Table 3-6).

Within the CWRS class, Intrepid (39.9 gr), Alvena (39.3 gr) and Goodeve-VB (39.2 gr) had the highest TKW. In the CWAD class, the highest and lowest TKW were Brigade (44.7 gr) and Enterprise (38.8 gr), respectively (Table 3-6).

3.2.8. Protein content

The protein content of the cultivars varied between 9.4 and 15.2 (%). The CWRS cultivars Lillian (15.2%), Somerset (15%), Eatonia (15%), CDC Alsask (14.5%) and Journey (14.4%) had the highest protein content. The lowest protein content was observed in CWSWS cultivars including Sadash (9.4%), AC Andrew (9.9%), Bhishaj (10.1%) and AC Reed (10.2%) (Table 3-6).

Red Fife, one of the older cultivars (1885), showed the lowest protein content (11.6%) of the CWRS class (11.6%). Protein content in the CWAD class varied between 12.6-13.7 (%). DT570 and AC Avonlea both showed similar protein content (13.7%) and Brigade and AC Navigator had the lowest protein content (12.6 and 12.7% respectively) (Table 3-6).

3.3. Correlation

Correlation coefficients for 8 traits measured on 100 cultivars are shown in Table 3-8. Yield was strongly and positively ($P<0.001$) associated with height, days to maturity, lodging and thousand kernel weight. However, yield and protein content were strongly and negatively correlated. A significant negative correlation occurred between days to maturity and protein content, but lodging and protein content had a positive strong correlation (Table 3-8).

A strong positive correlation between thousand kernel weight with yield, days to heading, days to maturity and protein content was found. Protein content was negatively correlated with yield. Lodging was also positively and strongly correlated with yield and height. A strong positive relation between days to maturity with days to heading and yield was also observed. Test weight was not correlated with the other traits to any level (Table 3-8).

3.3.1. Correlation in the CWRS class

Table 3-9 shows the correlation coefficients for 8 traits measured on 62 cultivars of the CWRS class. Yield was strongly and positively correlated with height, days to maturity, test weight and thousand kernel weight; and strongly and negatively correlated with protein content. Days to maturity was strongly and positively correlated with yield, days to heading, test weight and thousand kernel weight but negatively and strongly correlated with protein content. Lodging and days to maturity were also negatively correlated (Table 3-9).

3.4. Traits regression in the CWRS, CWAD and CPS classes

Regression plots of different traits (days to heading, height, days to maturity, yield, test weight, thousand kernel weight and protein content) versus the year of release of cultivars of the CWRS, CWAD and CPS classes are shown in Figure 3-1, 3-2 and 3-3 respectively. Slopes of these traits for CWRS, CWAD and CPS classes regressed over year are presented in Table 3-10. During 1885-2010, days to heading have slightly decreased for CWRS (-0.02 days per year) and CPS (-0.14 days per year) (Table 3-10; Figure 3-1a, and 3-3a). On the contrary, a slight increase in days to heading for the CWAD class (+0.08 days per year) was observed (Table 3-10; Figure 3-2a).

Plant height showed a gradual decrease in cultivars belonging to the CWRS (-0.15 cm per year) and CWAD class (-0.25 cm per year) (Table 3-10; Figure 3-1b, and 3-2b) but an increase in cultivars belonging to the CPS class (0.44 cm per year) (Table 3-10; Figure 3-3b). A decreasing trend for days to maturity for the CWRS class was observed, whereas an increasing trend was found for CWAD (Table 3-10; Figure 3-1c, and 3-2c). However, no clear trend between days to maturity and year of release was observed for the CPS class (Table 3-10; Figure 3-3c). Grain yield had increased significantly over the years for all the classes (Figure 3-1d, 3-2d and 3-3d), +12.66 Kg ha^{-1} per year for CWRS class and +57.6 Kg ha^{-1} per year for CPS class (Table 3-10). Test weight also showed an increasing trend for all of these classes (+0.02 Kg hL^{-1} per year for CWRS, +0.05 Kg hL^{-1} per year for CWAD, +0.13 Kg hL^{-1} per year for CPS) (Table 3-10; Figure 3-1e, 3-2e and 3-3e). Thousand kernel weight also increased in three classes over the years (+0.062 gr per year for CWRS, +0.048 gr per year for the CWAD, +0.16 gr per year for CPS) (Table 3-10; Figure 3-1f, 3-2f and 3-3f). Grain protein content showed an increasing trend for CWRS (+0.006 per year) and CPS (+0.095 per year) classes, but a decreasing trend in the CWAD class (-0.03 per year) (Table 3-10; Figure 3-1g, 3-2g and 3-3g).

3.5. Disease resistance

Least-square mean values and rating for leaf rust and yellow rust resistance as well as the resistance genes of 100 wheat cultivars grown during 2012-2013 in Edmonton (leaf rust) and in Lethbridge and Creston (yellow rust) are presented in Table 3-11. The reactions of the CWRS wheat cultivars with leaf rust ranged from highly resistant to susceptible. In this class, 5 cultivars were susceptible, 22 cultivars were moderately susceptible, 16 were moderately resistant, 17 were resistant and 2 were very resistant to leaf rust. CWAD cultivars showed high resistance levels to leaf rust where 9 were highly resistant and 5 cultivars were resistant. In the CPS class, 2 cultivars were susceptible, 3 were moderately susceptible, 2 showed moderate resistance and 2 were resistant to leaf rust. The CWES class cultivars were susceptible to leaf rust except Burnside which showed a moderate resistance. The CWSWS class cultivars were all moderately susceptible or susceptible to leaf rust (Table 3-11).

As shown in Table 3-11, the reactions of CWRS class cultivars to yellow rust varied between highly resistant and susceptible. In this class, 11 cultivars were moderately susceptible, 22 were moderately resistant, 22 were resistant and 7 cultivars were highly resistant to yellow rust. In this study, CWAD, CPS, CWES and CWSWS cultivars showed a suitable resistance (moderate to high) to yellow rust (Table 3-11).

4. Discussion

Due to the short growing seasons (95-125 d), long days (>14 h), and low temperatures early and late in the growing season typical in central and northern regions of the prairies, the development of early flowering and maturing cultivars is important in order to avoid frost damage which results in low yield and poor quality (Townley-Smith 1986). Early maturing cultivars are also found to be less prone to pre-harvest sprouting (Hucl and Matus-Cadiz 2002).

Despite having differences among genotypes in 100 cultivars grown during these years, environment had the highest effect on their days to heading (50.8%) and maturity (54.4%) (Table 3-3). It is known that flowering and maturity are delayed by low temperature and a cooler environment (Gardner et al. 1985). Din et al. (2010) found that higher temperature decreased the growth and development of wheat plants. Early maturity due to high temperature is known to be one of the factors reducing the yield in wheat (Inamullah et al. 2011). Due to a desirable temperature and precipitation level during these years in three locations, days to heading of the cultivars (54.4-61.9 d) and days to maturity (93.1-106.4) meet the optimal days to heading and maturity (Table 3-6). Usually dry and warm weather in the month of August promotes earlier maturity of wheat cultivars and thus precipitation at the end of the growing season leads to a longer time to maturity. In 2013 a high precipitation level was recorded in Edmonton and St. Albert in August (Table 3-2), which is expected to result in longer days to maturity.

The other factors affecting the days to heading and maturity are photoperiod, vernalization and earliness per se genes which are all genotypic characteristics (Kosner and Pankova 1998). Before the mid-1980s most Canada Western Hard Red Spring (CWRS) wheat cultivars were photoperiod sensitive (PS) (Hucl 1995). However, more than 20% of the recent CWRS cultivars in western Canada are described as photoperiod insensitive (PI) (Dyck et al.

2004). The PI feature leads to a minimum days to heading and maturity. In this trial, the earliest days to heading and maturity were observed in CWRS cultivars the majority of which are known to be photoperiod insensitive. There is a general negative correlation between cultivars with short days to heading and maturity, lower yields (Din et al. 2010). This was observed in the present study for all cultivars and for the CWRS class in particular. Greater days to heading and maturity (along with lower protein %) in the CPS class resulted in higher yields (20% more than CWRS class on average). The latest maturing cultivar in CWAD class, DT570 (106.4 days), had a very high average yield (4541 Kg ha^{-1}) (Table 3-6).

Genetics mainly influence the plant height in wheat cultivars, but height is also strongly affected by the environment (Clarke and DePauw 1993). The results obtained in this study suggest that genetics had the highest effect (28.3%) on plant height (Table 3-3). In this study the shortest cultivars were found in the CWAD and CPS classes (80 cm); they would therefore be classified as semidwarf. Usually semidwarfs have a high yield potential due to their better lodging resistance and greater sink size (Fischer et al. 1998).

Plant height is a major contributor towards lodging resistance (Keller et al. 1999; Kelbert et al. 2004a). In the present research lodging was also influenced mainly by genetic effects (31.6%) followed by environment (25.2%) (Table 3-3). The main source of lodging tolerance in wheat is the presence of height reducing (*Rht*) genes (Navabi et al. 2006). In the absence of *Rht* genes, lodging tolerance is influenced by straw strength (Kelbert et al. 2004b) where taller cultivars can be lodging resistant due to increased straw strength (Navabi et al. 2006). The highest incidence of lodging occurred in the two old tall cultivars of the CWRS class (Marquis and Garnet) and this was likely the result of the absence of *Rht* genes and low straw strength.

Among the different effects partitioned in the analyses of the present study, environmental effects had the biggest impact on grain yield. Precipitation amount is a key climatic factor affecting grain yields in semiarid regions (McCaig and DePauw 1995). In cool environments, wheat cultivars normally exhibit better vegetative growth and greater yields. As reported by Richards et al. (2001), in cooler climates with sufficient moisture (precipitation or irrigation) during the wheat growing season, higher yield may be obtained. Finlay et al. (2007) reported greater grain yields in cool and wet conditions (average growing season temperature and precipitation range 12.9-16 °C and 225-370 mm, respectively) relative to warm and dry conditions (average growing season temperature and precipitation 16.5-19.2 °C and 81-200 mm respectively). Based on this classification, the environmental conditions of the three locations of this study during 2011-2013 could be considered cool and wet in some environments, but cool and dry in others (Table 3-1, 3-2).

When maturity is delayed for a few days in a cool environment, cereal crops generally have a longer time for producing assimilates and transferring a larger amount of them to sink (grains), which results in increased grain yield (Gardner et al.1985). The highest yield in this trial was found in the CWSWS and CPS classes, both exhibiting relatively late maturity (Table 3-6).

The lowest yielding cultivars in this experiment were in the CWRS class due to the strict quality requirements for registration in this class. The yield advantage of CPS and CWSWS classes, compared with the CWRS class, is partially due to their lower protein concentration as well as the larger kernel size, which was required for the system of Kernel Visual Distinguishabilty that was abolished in 2008 (Wang et al. 2002). Lower protein requirements and greater kernel size guidelines for the CPS and CWSWS classes play an important role in their higher grain yields.

The Western Bread Wheat Co-operative (WBWC) test is a pre-registration test for lines considered for registration as CWRS cultivars. Several recently registered entries in this test have exhibited higher grain yield than earlier cultivars (Wang et al. 2002). Recent cultivars are required to maintain or improve grain and flour protein as well as dough strength relative to old cultivars (Wang et al. 2002). In the present, within the CWRS class, the highest grain yielding cultivars were CDC Go, CDC Stanley, BW423 and Muchmore (recent cultivars) while the lowest yielding were the older cultivars Garnet, Marquis and Thatcher (early cultivars) (Table 3-6). Both yield level groups of this class had similar protein content (~ 13%) despite having different grain yields.

Test-weight, as an important yield component, is a crucial grading factor in Canada and other countries since a high test weight indicates sound grain and high flour yield (Marshall et al. 1986; Finney et al. 1987). Environment had the highest effect (44.4%) on test weight in this trial (Table 3-3). High precipitation often delays the harvest and reduces the wheat grade due to a decrease in test-weight (Gan et al. 2000). There was no direct effect of test weight on grain yield in the present study. Higher yielding cultivars may be expected to exhibit higher test weights, although CWRS cultivars must have a higher test weight to fulfill the quality requirements of registration. In the present study, for example, CPS cultivars had higher grain yield than CWRS, but lower test weight, on average (Table 3-6). According to Gan et al. 2000, the required test-weight range for grading in the CWAD class needs to be higher (77-79 Kg hL^{-1}) than in the CPS (75-77 Kg hL^{-1}) class, but contradictory results in this experiment CWAD showed the lowest test weight (70.2 Kg hL^{-1}) among other classes. This may be because CWAD is not considered to be adapted to the Edmonton region and is normally grown in the very dry southern regions of Alberta and Saskatchewan.

Thousand kernel weight is a yield component which usually has a strong influence on gain yield. In this study it was found that CWES cultivars which had the highest thousand kernel weight also showed a high grain yield. CWRS cultivars with the lowest thousand kernel weight also exhibited the lowest grain yield (Table 3-6).

Since many factors including genetics, temperature, moisture and available nitrogen influence the protein content, it is always difficult to interpret protein content (Altenbach et al. 2003). Prolonged, heavy rains at the end of the growing season tend to decrease protein content (Derera 1980; Matsuo et al. 1982; Edwards et al. 1989). Also higher temperature leads to higher protein content in wheat. In the present study the environment had the highest effect on protein content. Since temperature and humidity during 2011-2013 in three locations were good for wheat production, average protein content (13.4%) was also desirable and acceptable. As expected, CWRS cultivars exhibited the highest protein content in this study, mainly due to the strict requirements for their registration in western Canada. The lowest protein content among all cultivars was found in CWSWS class due to its high yield and quality requirements of low protein and weak dough for cookie and cake flour (Table 3-6). Soft white spring wheat (CWSWS) is a high yield wheat class with a soft kernel and very low protein concentration (Canadian Wheat Board 2007). Also semidwarfs tend to have lower protein content than taller cultivars (McClung et al. 1986). Similar results were found in this research where CPS and CWAD classes both exhibited lower protein content than the CWRS class.

Traits of wheat may be correlated with each other positively or negatively. The direction of correlation can vary from an environment to another (DePauw et al. 2007). In accordance with the findings of Donmez et al. (2001) and in contrast with the findings of (Inamullah et al. 2011), a significant positive correlation between plant height and grain yield was observed in this study

(Table 3-8). In addition, plant height was strongly and positively correlated with lodging scores. This meant that shorter plants had higher resistance against lodging as previously reported by Kelbert et al. (2004a). Lodging was not with grain yield (r = 0.1) which is different than previously reported strong negative correlation between these two traits (due to greater difficulty harvesting at the end of the season), suggesting that most of the cultivars did not lodge in the present study.

A strong positive correlation between grain yield and time to maturity was observed, which is similar to the findings of Iqbal et al. (2007) who studied the genetic relationship between maturity, grain yield and protein content in a population of 130 early maturing spring wheat. This relationship is not suitable in production environments with a terminal abiotic stress (heat, drought, frost) (DePauw et al. 1981; van Ginkel et al. 1998). This positive correlation is also very challenging to wheat breeders in western Canada due to frost and pre harvest sprouting at the end of the growing season (Hucl and Matus-Cadiz 2002).

Days to maturity and thousand kernel weight were strongly and positively correlated in this trial. Later maturity also had led to a higher thousand kernel weight and greater yield. A positive correlation between grain yield and yield component traits such as plant height (Leilah and Al-Khateeb, 2005), thousand kernel weight (Leilah and Al-Khateeb, 2005), days to heading and test weight (Dogan et al. 2009) has been observed in previous studies. Similarly height and thousand kernel weight were positively associated with grain yield in the present study. A positive correlation between thousand kernel weight and test weight was reported earlier in several studies (Ghaderi et al. 1971; Tkachuk and Kuzina 1979; Matsuo and Dexter 1980; Marshall et al. 1986; Sissons et al. 2000). Similarly, a positive correlation (r = 0.51) between thousand kernel weight and test weight was found in the CWRS class but this was not the case for all the cultivars studied (Table 3-9).

The correlation between grain yield and protein content can be close to zero, negative or even positive within a wheat cultivar; where this relationship depends on environment as well as soil fertility (Kramer 1979; Terman 1979). Grain yield and protein content were negatively correlated to each other in this study (Table 3-8). The correlation value (-0.41) was within the range of correlation values (-0.2 to -0.8) reported previously (Costa and Kronstad 1994; Guthrie et al. 1984; Halloran 1981; Loffler and Busch 1982; O'Brien and Ronalds 1984). This negative correlation is an undesirable relationship since the protein content is positively correlated with bread loaf volume. This is observed in CWRS cultivars having high protein contents but relatively low yields (Table 3-9). However, the negative relationship between grain yield and protein content is desirable for the development of high yielding, low protein content wheat cultivars such as CPS and CWSWS used in confectionary products (DePauw et al. 2007).

The increase of yield in CWRS, CWAD and CPS cultivars during the years of their release can be related to environment, management and also genetic changes (McCaig and DePauw 1995). Precipitation is a main climatic factor affecting yields in the semiarid region. Short term variation in yields can be explained mainly by differences in precipitation (McCaig and DePauw 1995). During 2011-2013 sufficient precipitation was recorded in three locations of this study and there was no drought leading to yield loss (Table 3-2). Breeding efforts have led to an increase in the yield of recent cultivars in all of these classes. Yield increases in the CPS class have been more than the CWRS class owing to the strict registration requirements for end-use quality of CWRS. In addition, CWRS cultivars are planted over a broader geographical area than

CPS and CWAD cultivars. The CWRS cultivars need to ensure regional adaptation to any specific environment with its possible diseases (McCaig and DePauw 1995).

Recent studies show that yield increase during recent years has been related to an increase of kernel weight (Thomas and Graf 2014.). Thomas et al. (2013) showed that recent high-yielding CWRS cultivars (Shaw VB, Unity VB and Vesper VB) had increased kernel weights. Similarly, the strong correlation of thousand kernel weight and yield in the CWRS class revealed that yield increase is highly affected by kernel weight (Table 3-9). Highest yielding cultivars in the CWRS class include CDC Go (2003), CDC Stanley (2009), Muchmore (2009), in the CWAD class they include Brigade (2008), CDC Veron (2008), and in the CPS class they include HY682 (2009) and 5702PR (2007). These are all among recently developed cultivars and their high yield can be attributed to breeding efforts (Table 3-6).

Days to heading generally decrease due to breeding programs exploiting early heading genes (Worland, 1996). In the present trial days to heading and maturity decreased over the years in CWRS and CPS classes due to the breeding. This is an essential feature of the climate of central and northern region of the prairies, where the short growing season limits such areas to only early maturing cultivars (Townley-Smith 1986). Contrary to the other two classes, days to heading and maturity in the CWAD class showed an increase over the years. Due to the longer growing season in southern Alberta and Saskatchewan where, CWAD cultivars are grown, longer days to heading and maturity are desirable to achieve higher yields.

Conflicting results had been reported for the trends in kernel weight and test weight due to breeding. Heavier kernels as a result of breeding efforts have been reported previously by several research groups (Cox et al. 1988; Gymer 1981; Wych and Stuthman 1983). However, contradictory trends were found by other researchers (Hesselbach 1985; Perry and D’Antuono

1989; Sinha et al. 1981). Some researchers also reported a reduction in test weight as a result of breeding efforts (Abeledo et al. 2002; Araus et al. 2007; Blumler 1998; Moragues et al. 2006; Munoz et al. 1998) (4). In the present study, modern cultivars of CWRS, CWAD and CPS exhibited increased test weight and kernel weight indicating effective breeding for the correlated trait of grain yield increase.

DePauw et al. (2007) reported that within the CWRS class, grain yield had increased without diminishing protein content. They reported that the negative correlation between these two traits had been shifted slightly rather than broken. In this study, we found a general yield increase over years of breeding without protein diminishment for both the CWRS and CPS classes. Breeding has resulted in shorter plants with high resistance to lodging in all classes. Leaf rust resistance genes lead to plant protection from the pathogen, but often this resistance has not been as effective as the protection found in stem rust resistance genes. The leaf rust resistance genes include *Lr1*, *Lr10*, *Lr13*, *Lr14a*, *Lr16* and *Lr34* (McCallum et al. 2007a). Old CWRS cultivars including, Red Fife, Marquis, Thatcher, Neepawa and most others were moderately susceptible to leaf rust. Modern cultivars showed a better resistance to leaf rust due to the effectiveness of breeding programs. The breeding efforts during past years led to the discovery of resistance genes and their incorporation into new wheat germplasm (Martens et al. 2014). In this trial two of the highly resistant cultivars were Carberry and 5602HR, both carrying the *Yr18* gene which is linked to *Lr34* (Table 3-11).

According to McCallum et al. (2011) the CWRS cultivars such as Laura, Roblin, CDC Teal, AC Cadillac and AC Elsa carrying the resistance gene *Lr34* showed a partial level of resistance to leaf rust. However, in this study these cultivars except Laura, were moderately susceptible to leaf rust (Table 3-11). As stated by Martens et al. (2014), the partial resistance to leaf rust due to the presence of *Lr34* varied from year to year and this depended on the environment and leaf rust severity. This effect might be the reason for a lower leaf rust resistance in this trial. McKenzie, 5500HR, 5600HR, CDC Alsask and Lovitt showed an intermediate resistance or resistance to leaf rust due to the presence of the *Lr21* and *Lr22a* genes (Table 3-11), both discovered in Canada and which were known to be the reasons for leaf rust resistance (Rowland and Kerber 1974). In the present study, the CPS cultivars 5700PR, 5701PR and 5702PR and also CWES cultivar Burnside showed an intermediate resistance due to the presence of the *Lr34*/*Yr18* genes (Table 3-11).

Yellow rust resistance genes include *Yr10*, *Yr17*, *Yr18* and *Yr36* (Randhawa et al. 2012). Lillian, AC Intrepid, AC Elsa and AC Cadillac from the CWRS class exhibited high resistance to yellow rust (Table 3-11). The resistance in Lillian is explained by the presence of adult plant resistance (APR) genes *Yr18* and *Yr36* (Randhawa et al. 2012). The rest of these highly resistant cultivars carry the *Yr18* gene only. The yellow rust resistant cultivar, CDC Teal, carrying *Yr18* (Randhawa et al. 2012), was susceptible to yellow rust in this study (Table 3-11). This might be due to the environmental conditions (especially temperature) known to be an effective factor in yellow rust resistance (Line and Chen 1995), or yellow rust pressure in this research. It may also point to the necessity of modifying genes in addition to the major adult plant resistant gene *Yr18.*

In the CWAD cultivars, resistance to yellow rust ranged from intermediate to high in this trial. Stripe rust resistance in durum wheat is not well understood, however, both seedling and adult plant resistance genes have been known to be influential factors (Ma et al. 1997; Randhawa et al. 2012). In the CPS class, 5701PR and HY682 showed a high resistance to yellow rust, where the former (5701PR) carries *Yr18*. The resistance of Burnside from the CWES class can be attributed to the APR genes *Yr18* and *Yr36*. CWSWS cultivars Bhishaj and Sadash exhibited a suitable yellow rust resistance in this study, which was similar to the findings of Randhawa et al. (2012).

Conclusions:

Western Canadian wheat breeding from 1885 on has altered many different agronomic traits: improving yield, protein content, days to maturity and disease resistance. This thesis studied the progressive effects of breeding programs on different traits. The results demonstrate that new cultivars have a higher grain yield compared with early cultivars. In the CWRS class, the most important class of western Canada wheat, breeding had led to increased grain yield while the protein content has been maintained or even showed a slight increase. Improvements in the protein content of the high yield and low protein content wheat classes through breeding was also confirmed in this study. Due to the short growing season in western Canada, breeding has resulted in earlier maturity, especially in recent cultivars of the CWRS class. The most effective way to control rust in western Canada has been through developing resistant cultivars through breeding for genetic resistance.

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Table 1-1. Description of western Canada spring wheat classes.

Class	Description	Application
Canadian Western Red Spring (CWRS)	Known as hard red spring wheat. Largest group in western Canada. A hard wheat with superior milling and baking properties due to its high water absorption and strong gluten. Mean grain protein content of 13.6%.	Production of high volume of pan bread and used extensively, alone or blends with other wheats for hearth bread, noodles, flat breads and steam breads.
Canadian Western Amber Durum (CWAD)	Hard vitreous kernels providing high yield semolina. Protein content of less than 13.5%.	Production of semolina for pasta, couscous, and for durum bread in the Mediterranean region.
Canadian Prairie spring Red (CPSR)	High yield 25-30% >CWRS. High protein content, 1-2%<CWRS.	Making flat breads, hearth breads, noodles and associated products. widely used domestically in Canadian feed industry because of its high yield.
Canadian Prairie Spring White (CPSW)	A medium-strength wheat with white kernels.	Used for producing flat breads, noodles, chapattis and related goods.
Canadian Western Extra Strong (CWES)	A hard red wheat with extra-strong gluten. Protein content is slightly lower than cultivars of CWRS class.	Suitable for blending with weaker flours, use in frozen dough and for making special breads.
Canadian Western Soft White Spring (CWSWS)	Soft white spring wheat Low protein content generally under 10.5% .Weak dough properties.	Suitable for the production of cakes, cookies and pastry as well as flat breads, noodles and the like.
Canadian Western Hard White Spring (CWHWS)	Hard white spring wheat. Superior milling quality producing flour with excellent color. Dough strength suitable for both bread products and noodles.	Production of bread and noodles.
Canadian Western General Purpose (CWGP)	Cultivars in this class are high-yielding and have high starch and low protein content	Suitable for industrial uses such as ethanol production or animal feed.

(Canadian Grain Commission; DePauw and Hunt 2001)

Table 1-2. Some information about recent cultivars of CWRS class.

Name	**Year registered**	**Breeding Institution**	**Primary trait**
McKenzie	1997	Viterra	Higher yield, resistance to leaf rust
Superb	2001	AAFC, Winnipeg	Higher yield
Lillian	2003	AAFC, Swift Current& Winnipeg	Resistance to wheat stem sawfly, Higher yield, *Gpc-B1*/*Yr36*, *Lr34*/*Yr18*
Alvena	2006	AAFC, Swift Current	Earlier maturity
CDC Abound	2007	CDC, University of Saskatchewan	Resistance to imidazolinone herbicides
Waskada	2007	AAFC, Winnipeg	Improved resistance to FHB
Stettler	2008	AAFC, Swift Current	Higher yield and protein
Shaw	2009	AAFC, Winnipeg	Resistance to orange wheat blossom midge *Sm1*
Carberry	2009	AAFC, Swift Current	Improved resistance to FHB, and higher yield and protein
Muchmore	2009	AAFC, Swift Current	Higher yield

(DePauw et al. 2011)

Table 2-1. Description of 100 western Canadian spring wheat cultivars from 7 classes used in trials conducted during 2011-2013 at three locations.

Cultivar	Year of release	Class	Origin
Red Fife	1885	CWRS	Peterborough, ON from Danzig, Poland
Marquis	1910	CWRS	Agriculture Canada, Ottawa, ON
Garnet	1925	CWRS	Agriculture Canada, Ottawa, ON
Thatcher	1935	CWRS	University of Minnesota
Park	1963	CWRS	Agriculture Canada, Lacombe, AB
Neepawa	1969	CWRS	Agriculture Canada, Winnipeg, MB
Columbus	1980	CWRS	Agriculture Canada, Winnipeg, MB
Kane	1981	CWRS	Agriculture Canada, Winnipeg, MB
Katepwa	1981	CWRS	Agriculture Canada, Winnipeg, MB
Laura	1986	CWRS	Agriculture Canada, Swift Current, SK
Roblin	1986	CWRS	Agriculture Canada, Winnipeg, MB
CDC Teal	1991	CWRS	Crop Development Center, Saskatoon, SK
CDC Merlin	1992	CWRS	Crop Development Center, Saskatoon, SK
AC Domain	1993	CWRS	Agriculture Canada, Winnipeg, MB
Eatonia	1993	CWRS	Agriculture Canada, Swift Current, SK
AC Barrie	1994	CWRS	Agriculture Canada, Swift Current, SK
AC Cadillac	1996	CWRS	Agriculture Canada, Swift Current, SK
AC Elsa	1996	CWRS	Agriculture Canada, Swift Current, SK
AC Intrepid	1997	CWRS	Agriculture Canada, Swift Current, SK
AC Splendor	1997	CWRS	Agriculture Canada, Winnipeg, MB
McKenzie	1997	CWRS	Saskatchewan Wheat Pool
AC Abbey	1998	CWRS	Agriculture Canada, Swift Current, SK
Prodigy	1998	CWRS	Saskatchewan Wheat Pool
5600HR	1999	CWRS	UGG research farm
CDC Bounty	1999	CWRS	Crop Development Center, Saskatoon, SK
5500HR	2000	CWRS	UGG Research Farm
5601HR	2001	CWRS	AgriPro / UGG
AC Superb	2001	CWRS	Agriculture Canada, Winnipeg, MB
CDC Imagine	2002	CWRS	Crop Development Center, Saskatoon, SK
Journey	2002	CWRS	Saskatchewan Wheat Pool
Lovitt	2002	CWRS	Agriculture Canada, Swift Current, SK
CDC Go	2003	CWRS	Crop Development Center, Saskatoon, SK
CDC Osler	2003	CWRS	Crop Development Center, Saskatoon, SK
PT 559	2003	CWRS	U Saskatchewan, Crop Development Centre
5602HR	2004	CWRS	Agricore United/Proven Seed
CDC Alsask	2004	CWRS	U Saskatchewan, Crop Development Centre
Harvest	2004	CWRS	Agriculture Canada, Winnipeg, MB
Infinity	2004	CWRS	Agriculture Canada, Swift Current, SK
Lillian	2004	CWRS	Agriculture Canada, Swift Current, SK
Somerset	2005	CWRS	Agriculture Canada, Winnipeg, MB
Somerset	2005	CWRS	Agriculture Canada, Winnipeg, MB
Alvena	2006	CWRS	Agriculture Canada, Swift Current, SK
CDC Abound	2006	CWRS	U Saskatchewan., Crop Development Centre
Helios	2006	CWRS	Agriculture Canada, Swift Current, SK
Fieldstar VB	2007	CWRS	Agriculture Canada, Winnipeg, MB

Cultivar	Year of release	Class	Origin
GoodeveVB	2007	CWRS	Agriculture Canada, Swift Current, SK
Unity VB	2007	CWRS	Agriculture Canada, Winnipeg, MB
Waskada	2007	CWRS	Agriculture Canada, Winnipeg, MB
5603HR	2008	CWRS	Syngenta
859CL	2008	CWRS	Syngenta
Stettler	2008	CWRS	Agriculture Canada, Swift Current, SK
5604HR CL	2009	CWRS	Syngenta
Carberry	2009	CWRS	Agriculture Canada, Swift Current, SK,
CDC Kernen	2009	CWRS	Crop Development Center, Saskatoon, SK
CDC Stanley	2009	CWRS	Crop Development Center, Saskatoon, SK
CDC Thrive	2009	CWRS	Agriculture Canada, Winnipeg, MB
CDC Utmost	2009	CWRS	Crop Development Center, Saskatoon, SK
Glenn	2009	CWRS	NDSU/Canterra
Muchmore	2009	CWRS	Agriculture Canada, Swift Current, SK
Shaw	2009	CWRS	Agriculture Canada, Winnipeg, MB
BW423	2010	CWRS	Crop Development Center, Saskatoon, SK
Vesper	2010	CWRS	Agriculture Canada, Winnipeg, MB
PT580	2011	CWRS	Crop Development Center, Saskatoon, SK
Kyle	1984	CWAD	Agriculture Canada, Swift Current, SK
AC Morse	1996	CWAD	Agriculture Canada, Winnipeg, MB
AC Avonlea	1997	CWAD	Agriculture Canada, Swift Current, SK
AC Navigator	1999	CWAD	Agriculture Canada, Swift Current, SK
Napolean	2001	CWAD	Agriculture Canada, Winnipeg, MB
Commander	2004	CWAD	Agriculture Canada, Swift Current, SK
Strongfield	2004	CWAD	Agriculture Canada, Swift Current, SK
Brigade	2008	CWAD	Agriculture Canada, Swift Current, SK
CDC Verona	2008	CWAD	University of Saskatchewan
Eurostar	2008	CWAD	Agriculture Canada, Swift Current, SK
Enterprise	2009	CWAD	Agriculture Canada, Swift Current, SK,
Transcend	2010	CWAD	Agriculture Canada, Swift Current, SK
DT570	.	CWAD	Crop Development Center, Saskatoon, SK
DT780	.	CWAD	Agriculture Canada, Swift Current, SK,
AC Taber	1991	CPS	Agriculture Canada, Swift Current, SK
AC Foremost	1995	CPS	Agriculture Canada, Swift Current, Lethbridge
AC Crystal	1996	CPS	Agriculture Canada, Swift Current, SK
AC Vista	1996	CPS	Agriculture Canada, Swift Current, SK
5700PR	2000	CPS	AgriPro / UGG
5701PR	2001	CPS	AgriPro / UGG
5702PR	2007	CPS	Syngenta
HY682	2009	CPS	Agriculture Canada, Winnipeg, MB
SY985	2010	CPS	Syngenta
Glenlea	1972	CWES	Agriculture Canada, Winnipeg, MB
CDC Rama	2001	CWES	Crop Development Center, Saskatoon, SK
CDC Walrus	2003	CWES	Crop Development Center, Saskatoon, SK
Burnside	2004	CWES	Agriculture Canada, Winnipeg, MB
Glencross VB	2007	CWES	Agriculture Canada, Swift Current, SK
CDC Bison	2008	CWES	Agriculture Canada, Winnipeg, MB
AC Reed	1991	CWSWS	Agriculture Canada, Lethbridge, AB
AC Andrew	2000	CWSWS	Agriculture Canada, Lethbridge, AB
Bhishaj	2003	CWSWS	Agriculture Canada, Lethbridge, AB

Cultivar	Year of release	Class	Origin
Sadash	2007	CWSWS	Agriculture Canada, Lethbridge, AB
Minnedosa	2008	CWGP	Agriculture Canada, Winnipeg, MB
NRG003	2009	CWGP	Crop Development Center, Saskatoon, SK
NRG010	2009	CWGP	Agriculture Canada, Swift Current, SK
Snowbird	2000	CWHWS	Agriculture Canada, Winnipeg, MB
Snowstar	2006	CWHWS	Agriculture Canada, Winnipeg, MB

Table 3-1. Mean temperature 2011 to 2013 in three locations.

Trait	Location	Year	May	June	July	August	September	Annual mean
Temperature (°C)	Edmonton	2011	13	15	17	17	14	15
		2012	12	17	20	18	14	16
		2013	14	15	17	18	14	16
	Saskatoon	2011	11	16	18	17	15	15
		2012	10	16	20	17	13	15
	St. Albert	2013	14	15	17	18	15	16

Table 3-2. Mean and total annual precipitation 2011 to 2013 in three locations.

Trait	Location	Year	May	June	July	August	September	Total annual precipitation
Precipitation (mm)	Edmonton	2011	12	140	114	21	15	302
		2012	46	28	135	29	14	252
		2013	36	124	87	109	9	356
	Saskatoon	2011	18	94	69	17	6	204
		2012	108	121	81	49	1	359
	St. Albert	2013	31	118	85	110	5	349

Table 3-3. Percent sums of squares within fixed effects analysis of variance for days to heading, height, days to maturity, lodging, grain yield, test weight, thousand kernel weight and protein content, of 100 wheat cultivars grown during 2011-2013 at three locations in western Canada.

Source	Height	Days to heading	Days to maturity	Lodging	Yield	Test weight	Thousand kernel weight	Protein content
Env (%)	20.7**	50.8**	54.4**	25.2**	57.2**	44.0**	49.6**	46.5**
Rep (Env) (%)	20.5**	0.7**	1.9*	1.1*	2.9**	0.4*	1.3**	1.6**
Blk (Rep*Env) (%)	20.1**	2.7**	19.5**	5.4**	5.6**	2.1**	2.8**	2.1**
Cultivar (%)	28.3**	21.4**	17.7**	31.6**	15.4**	24.5**	34.1**	36.7**
Cultivar*Env (%)	6.0**	14.5**	19.5 **	23.9**	11.9**	21.5**	8.2**	8.4**
Error	4.4	9.9	6.2	13.0	7.0	7.5	4.1	4.7

Values significant at *$P < 0.05$, ** $P < 0.001$, ns: non-significant

Table 3-4. Percent sums of squares within fixed effects analysis of variance for days to heading, height, days to maturity, lodging, grain yield, test weight, thousand kernel weight and protein content, of 62 CWRS cultivars grown during 2011-2013 at three locations in western Canada.

Source	Height	Days to heading	Days to maturity	Lodging	Yield	Test weight	Thousand kernel weight	Protein content
Env	52.3**	38.5**	59.8**	23.6**	62.7**	50.2**	59.5**	63.2**
Rep (Env)	1.1**	4.3**	0.5*	1.8**	3.0**	0.7*	1.2*	2.1**
Blk (Rep*Env)	4.1**	5.0	3.5*	7.7**	7.0**	3.8*	5.7**	3.9**
Cultivar	16.3**	35.5**	11.8**	35.9**	8.3**	20.4**	20.7**	16.3**
Cultivar*Env	14.9**	9.2**	17.3**	19.9**	12.0**	16.9**	7.7**	9.2**
Error	11.4	7.4	7.1	11.2	7.0	8.0	5.4	5.4

Values significant at *P < 0.05, ** P < 0.001, ns: non-significant

Table 3-5. Percent sums of squares within fixed effects analysis of variance for days to heading, height, days to maturity, lodging, grain yield, test weight, thousand kernel weight and protein content, of 14 CWAD cultivars grown during 2011-2013 at three locations in western Canada.

Source	Height	Days to heading	Days to maturity	Lodging	Yield	Test weight	Thousand kernel weight	Protein content
Env	69.9**	41.3**	85.0**	24.1**	61.1**	65.1**	79.1**	73.7**
Rep (Env)	0.8*	4.2	0.3	1.9	6.4**	2.2*	2.6*	0.8
Blk (Rep*Env)	11.8*	18.3*	3.1	19.7	18.9	12.5	6.8	13.2*
Cultivar	1.8**	24.6	1.5	30.9**	3.0	6.6*	4.1	3.8*
Cultivar*Env	14.7*	10.2**	9.4**	20.4*	8.4	11.4	6.4	7.7*
Error	0.9	1.4	0.6	2.9	2.2	2.2	1.0	0.8

Values significant at *P < 0.05, ** P < 0.001, ns: non-significant

Table 3-6. Least-square mean values for days to heading, height, days to maturity, lodging, grain yield, test weight, thousand kernel weight and protein content, of 100 wheat cultivars grown during 2011-2013 at three locations in western Canada.

Cultivar	Year of release	Class	Height (cm)	Lodging (1-9)	Days to Heading (d)	Days to Maturity (d)	Protein content (%)	Yield (Kg ha^{-1})	Thousand kernel weight (gr)	Test weight (Kg hL^{-1})
Red Fife	1885	CWRS	118.9	4.16	61.9	106.3	11.6	3948	37.4	77.5
Marquis	1910	CWRS	115.2	4.25	60.0	100.6	14.1	3778	33.9	76.9
Garnet	1925	CWRS	110.2	5.00	55.1	94.6	13.3	3688	28.9	78.0
Thatcher	1935	CWRS	104.8	3.07	57.5	97.5	13.0	3921	31.6	76.9
Park	1963	CWRS	102.2	2.55	54.7	97.5	13.5	4243	32.6	77.1
Neepawa	1969	CWRS	104.3	2.19	57.5	97.9	13.2	4076	33.6	77.2
Columbus	1980	CWRS	110.9	1.56	59.0	99.8	14.0	4366	37.8	78.8
Kane	1981	CWRS	93.5	1.17	56.1	99.1	13.5	4963	35.4	79.9
Katepwa	1981	CWRS	102.9	2.40	57.1	96.4	13.8	4282	34.2	77.8
Laura	1986	CWRS	103.5	2.79	58.6	100.0	13.9	4203	32.1	77.8
Roblin	1986	CWRS	97.9	1.51	54.8	95.8	13.8	4255	34.6	76.0
CDC Teal	1991	CWRS	101.1	1.56	56.8	98.2	14.2	4952	36.6	77.9
CDC Merlin	1992	CWRS	107.0	1.99	58.0	100.9	13.7	4579	38.5	79.2
AC Domain	1993	CWRS	94.3	1.24	57.8	98.5	14.0	4108	33.4	78.0
Eatonia	1993	CWRS	103.0	3.58	59.2	99.9	14.9	4076	34.2	78.1
AC Barrie	1994	CWRS	99.2	1.51	57.6	98.4	13.4	4594	36.7	79.4
AC Cadillac	1996	CWRS	106.5	2.54	56.7	97.8	13.9	4751	36.8	80.2
AC Elsa	1996	CWRS	99.3	1.42	59.2	98.8	14.3	4567	33.0	77.6
AC Intrepid	1997	CWRS	101.9	1.59	56.0	95.2	13.6	4854	40.0	77.7
AC Splendor	1997	CWRS	103.4	2.43	54.4	93.1	14.1	4240	36.6	77.2
McKenzie	1997	CWRS	99.3	2.04	55.3	97.1	13.2	4646	33.7	78.6
AC Abbey	1998	CWRS	92.9	2.09	58.0	98.6	13.6	4903	37.7	78.6
Prodigy	1998	CWRS	106.2	1.63	58.6	98.0	14.3	4454	33.8	79.1
5600HR	1999	CWRS	108.8	1.50	59.2	99.0	13.4	4549	35.3	78.4
CDC Bounty	1999	CWRS	104.1	2.69	58.0	98.4	14.2	4450	37.7	80.4
5500HR	2000	CWRS	99.6	1.52	57.6	98.4	13.4	4518	37.2	74.7
5601HR	2001	CWRS	104.2	1.40	58.8	99.1	13.7	4430	35.8	78.4
AC Superb	2001	CWRS	92.8	1.18	56.8	100.9	12.6	5042	38.7	78.9
CDC Imagine	2002	CWRS	94.7	1.07	58.5	98.9	14.1	4801	37.2	77.8
Journey	2002	CWRS	96.7	1.20	58.1	98.5	14.4	4383	33.7	79.4
Lovitt	2002	CWRS	101.4	1.63	57.4	96.7	13.4	3988	34.0	78.0
CDC Go	2003	CWRS	87.7	1.09	55.7	101.0	13.4	5376	38.9	78.1
CDC Osler	2003	CWRS	98.6	1.92	56.9	96.5	14.1	4554	34.2	77.5
PT 559	2003	CWRS	101.0	1.82	55.3	96.7	14.0	4166	36.8	77.4
5602HR	2004	CWRS	97.3	1.60	57.8	99.2	13.7	4924	34.9	78.9
CDC Alsask	2004	CWRS	103.8	2.67	57.9	98.0	14.5	4898	36.8	78.1
Harvest	2004	CWRS	93.9	1.29	55.8	96.8	13.3	4719	35.8	78.5
Infinity	2004	CWRS	99.2	2.04	57.9	96.2	13.3	4412	33.8	77.8
Lillian	2004	CWRS	99.9	2.60	59.3	98.0	15.2	4635	37.9	78.0
Somerset	2005	CWRS	108.1	2.12	59.3	97.9	15.0	4681	38.6	76.9
Alvena	2006	CWRS	99.4	1.89	56.9	96.9	14.2	4828	39.5	79.3
CDC Abound	2006	CWRS	90.0	1.16	57.0	101.3	13.0	5084	37.5	78.5
Helios	2006	CWRS	98.9	1.82	56.1	97.8	13.0	4688	37.1	78.2
Fieldstar VB	2007	CWRS	102.7	2.21	57.2	97.8	13.6	4898	32.5	79.8

Cultivar	Year of release	Class	Height (cm)	Lodging (1-9)	Days to Heading (d)	Days to Maturity (d)	Protein content (%)	Yield (Kg ha^{-1})	Thousand kernel weight (gr)	Test weight (Kg hL^{-1})
GoodeveVB	2007	CWRS	98.2	1.68	58.1	99.2	13.9	4291	39.2	78.5
Unity VB	2007	CWRS	98.3	1.98	56.5	96.3	13.2	4833	34.5	79.7
Waskada	2007	CWRS	101.8	2.02	55.8	98.9	13.3	4746	35.6	80.2
5603HR	2008	CWRS	100.9	1.45	59.0	98.9	13.1	4927	32.6	79.1
859CL	2008	CWRS	91.8	1.65	56.2	101.2	13.6	4876	34.4	79.4
Stettler	2008	CWRS	94.3	1.21	59.2	101.1	14.1	4869	34.0	78.9
5604HR CL	2009	CWRS	95.0	1.47	55.5	97.6	12.9	4514	31.7	78.1
Carberry	2009	CWRS	85.3	0.99	55.8	103.7	13.1	4703	34.7	79.8
CDC Kernen	2009	CWRS	101.8	1.44	58.2	101.4	14.0	5169	37.1	78.7
CDC Stanley	2009	CWRS	96.3	1.14	57.2	99.3	13.4	5232	34.0	78.3
CDC Thrive	2009	CWRS	101.5	1.66	57.1	97.1	13.8	4725	34.7	78.4
CDC Utmost	2009	CWRS	94.9	1.48	56.9	96.4	13.2	4770	35.9	78.4
Glenn	2009	CWRS	93.9	1.26	56.6	103.8	13.6	4491	33.7	81.4
Muchmore	2009	CWRS	83.1	1.05	56.7	103.2	12.6	5092	35.9	78.7
Shaw	2009	CWRS	102.8	1.48	58.7	99.0	12.9	4980	35.9	79.1
BW423	2010	CWRS	98.1	1.71	59.2	97.9	13.5	5172	34.6	79.3
Vesper	2010	CWRS	96.8	1.45	57.3	99.5	12.7	4690	37.7	78.8
PT580	2011	CWRS	96.1	1.34	57.6	97.1	13.3	4880	34.2	79.2
Kyle	1984	CWAD	112.1	4.25	60.4	102.6	13.5	4050	41.7	76.6
AC Morse	1996	CWAD	92.8	1.05	58.8	104.4	13.1	4662	41.5	76.3
AC Avonlea	1997	CWAD	94.1	1.74	59.3	105.4	13.8	4200	40.7	76.2
AC Navigator	1999	CWAD	80.0	1.11	60.4	104.3	12.8	4014	41.6	76.3
Napolean	2001	CWAD	98.9	1.42	59.7	103.5	13.0	4934	44.3	76.6
Commander	2004	CWAD	80.3	1.23	60.5	102.3	12.8	4591	43.0	70.2
Strongfield	2004	CWAD	81.7	1.62	60.0	103.3	13.5	4036	40.9	115.9
Brigade	2008	CWAD	99.4	1.09	60.9	104.3	12.6	5074	44.7	78.2
Eurostar	2008	CWAD	96.0	1.00	59.5	105.9	13.5	4960	42.9	78.1
CDC Verona	2008	CWAD	98.2	1.59	60.6	104.0	12.8	4531	43.4	78.8
Enterprise	2009	CWAD	92.6	2.00	60.9	105.9	13.6	4314	38.7	77.2
Transcend	2010	CWAD	98.4	1.26	60.2	103.3	13.6	4376	41.6	76.7
DT570	.	CWAD	87.7	1.12	61.0	106.4	13.7	4318	40.1	76.3
DT780	.	CWAD	91.8	1.17	59.7	104.7	13.0	4547	39.6	75.5
AC Taber	1991	CPS	88.9	1.77	61.5	104.4	10.9	4490	38.6	75.4
AC Foremost	1995	CPS	80.1	1.71	59.4	102.1	11.2	5062	37.5	76.4
AC Crystal	1996	CPS	88.9	1.51	61.4	103.5	11.0	4184	36.2	75.9
AC Vista	1996	CPS(W)	90.5	1.88	58.0	100.5	11.6	5672	41.9	77.0
5700PR	2000	CPS	83.2	1.14	58.0	103.1	11.7	4889	39.2	78.0
5701PR	2001	CPS	86.3	1.52	59.4	101.3	12.1	5310	39.4	76.9
5702PR	2007	CPS	91.9	1.54	58.0	102.5	12.4	5615	40.0	75.3
HY682	2009	CPS	99.0	2.58	61.0	104.5	12.5	5907	39.7	79.4
SY985	2010	CPS	90.3	1.87	59.2	102.5	12.7	5412	42.2	78.1
Glenlea	1972	CWES	113.8	2.66	59.7	101.1	12.9	5378	46.6	78.8
CDC Rama	2001	CWES	109.2	1.90	58.3	103.1	13.5	5219	44.4	79.1
CDC Walrus	2003	CWES	105.2	2.70	60.1	100.7	13.1	5302	45.5	78.5
Burnside	2004	CWES	108.7	2.16	60.1	98.1	13.9	5302	44.2	79.2
Glencross VB	2007	CWES	110.1	2.52	58.4	96.7	13.5	5455	40.5	78.5
CDC Bison	2008	CWES	93.6	1.31	60.0	103.2	13.2	5625	45.2	78.4
AC Reed	1991	CWSWS	83.3	1.19	57.6	100.0	10.2	5412	34.3	75.3
AC Andrew	2000	CWSWS	90.7	1.22	60.8	102.7	9.9	6440	39.6	76.3
Bhishaj	2003	CWSWS	90.4	2.11	58.2	101.6	10.1	6120	34.8	76.0

Cultivar	Year of release	Class	Height (cm)	Lodging (1-9)	Days to Heading (d)	Days to Maturity (d)	Protein content (%)	Yield (Kg ha^{-1})	Thousand kernel weight (gr)	Test weight (Kg hL^{-1})
Sadash	2007	CWSWS	89.8	1.36	60.7	104.8	9.4	6298	34.4	77.3
Minnedosa	2008	CWGP	100.0	1.99	56.2	99.4	13.7	4468	38.6	77.7
NRG003	2009	CWGP	90.1	1.84	58.7	101.1	11.6	5487	43.5	77.0
NRG010	2009	CWGP	92.4	1.65	59.8	105.1	11.2	5634	38.9	77.0
Snowbird	2000	CWHWS	101.9	1.67	56.3	100.4	13.5	4673	33.7	78.1
Snowstar	2006	CWHWS	92.1	1.16	55.0	96.7	12.2	4091	30.8	78.8
SE			2.2493	0.3857	0.9047	1.9864	0.4	287	1.4517	5.7297
CV			4.14	32.16	2.74	2.29	3.7	9.63	4.76	1.14

Table 3-7. Mean values for all traits of 100 wheat cultivars grown during 2011-2013 at three locations in western Canada.

Trait	Mean	SD	Min	Max	CV
Days to heading (d)	57.84	±3.63	49	75	2.74
Height (cm)	98.36	±11.42	60	142	4.14
Days to maturity (d)	99.86	±6.68	86	132	2.29
Lodging (1-9)	1.87	±1.25	1	8	32.16
Yield (kg ha^{-1})	4817.99	±1284.78	1422	9632	9.63
Test weight (kg hL^{-1})	78.29	±15.7	0	669.1	1.14
Thousand kernel weight (gr)	36.77	±6.02	23.4	56.7	4.76
Protein content (%)	13.04	±1.74	7.85	18.8	3.7

Table 3-8. Correlation coefficients for 8 traits measured on 100 cultivars grown during 2011-2013 at three locations in western Canada.

Trait	Height	Days to heading	Days to maturity	Lodging	Protein content	Thousand kernel weight	Test weight
Yield	0.31**	0.036^{ns}	0.26**	0.10**	-0.41**	0.36**	0.007^{ns}
Height		-0.06*	-0.08*	0.50**	0.03^{ns}	0.35^{ns}	-0.02^{ns}
Days to heading			0.49**	-0.02^{ns}	0.046^{ns}	0.47**	0.006^{ns}
Days to maturity				-0.13**	-0.20**	0.54**	0.01^{ns}
Lodging					0.13**	-0.12*	-0.003^{ns}
Protein content						-0.21**	0.01^{ns}
Thousand kernel weight							-0.02^{ns}

Values significant at *P < 0.05, ** P < 0.0001, ns: non-significant

Table 3-9. Correlation coefficients for 8 traits measured on 62 cultivars of CWRS class grown during 2011-2013 at three locations in western Canada.

Trait	Days to heading	height	Days to maturity	Lodging	Yield	Test weight	Thousand kernel weight	Protein content
Days to heading	1	0.141**	0.337**	0.049	0.017	0.017	0.380**	0.239**
Height		1	0.015	0.499**	0.397**	0.074*	0.138*	-0.143**
Days to Maturity			1	-0.091*	0.261**	0.252**	0.493**	-0.117**
Lodging				1	0.082*	-0.015	-0.202**	0.068*
Yield					1	0.408**	0.524**	-0.295**
Test weight						1	0.511**	0.028
Thousand kernel weight							1	-0.134*
Protein content								1

Values significant at *P < 0.05, ** P < 0.0001, ns: non-significant

Table 3-10. Slopes of seven traits for CWRS, CWAD and CPS classes regressed on year.

Class/Trait	YIELD	HD	MAT	HT	TWT	TKW	PRO
CWRS	12.66 ±1.36Xy	-0.02±0.006	-0.02±0.006	-0.15±0.01	0.02±0.004	0.062±0.01	0.006±0.002
CWAD	-	0.08±0.023	0.09±0.03	-0.25±0.22	0.05±0.01	0.048±0.04	-0.03±0.006
CPS	57.6 ±13.75	-0.14±0.07	-	0.44±0.25	0.13±0.02	0.16±0.05	0.095±0.01

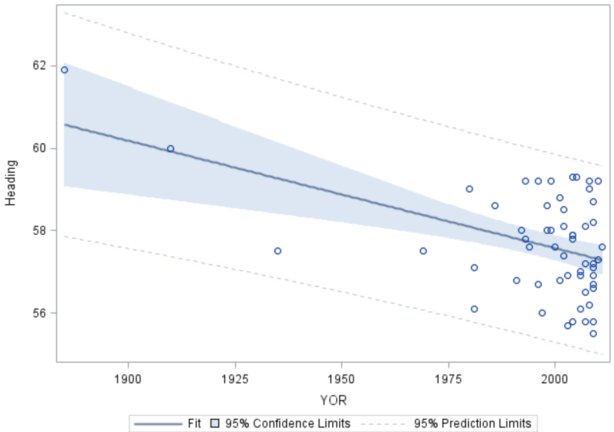
Table 3-11. Least-square mean values and rating for leaf rust and yellow rust resistance as well as the resistance genes of 100 wheat cultivars grown during 2012-2013 in three locations. S: Susceptible, MS: Moderately susceptible, MR: Moderately resistant, R: Resistant, VR: Very resistant.

Cultivar	Year of release	Class	Leaf rust (LSM)	Rating (Lr)	Gene(s) Lr	Yellow rust (LSM)	Rating (Yr)	Gene(s) Yr
Red Fife	1885	CWRS	7.0	MS	-	3.8	R	-
Marquis	1910	CWRS	6.5	MS	-	2.9	R	-
Garnet	1925	CWRS	7.5	MS	-	4.9	MR	-
Thatcher	1935	CWRS	8.5	S	*Lr22b*	6.3	MS	-
Park	1963	CWRS	7.5	MS	-	5.6	MR	-
Neepawa	1969	CWRS	8.0	MS	*Lr13*	4.9	MR	-
Columbus	1980	CWRS	6.0	MS	-	6.3	MS	-
Katepwa	1981	CWRS	4.0	MR	-	3.9	R	-
Kane	1981	CWRS	2.5	R	-	3.3	R	-
Roblin	1986	CWRS	6.3	MS	*Lr34*	2.3	R	-
Laura	1986	CWRS	4.0	MR	*Lr1, Lr10,Lr34*	2.1	R	*Yr 18*
CDC Teal	1991	CWRS	7.0	MS	*Lr1, Lr13,Lr34*	6.1	MS	*Yr 18*
CDC Merlin	1992	CWRS	8.0	MS	-	5.1	MR	-
Eatonia	1993	CWRS	8.5	S	-	3.3	R	*Yr 18*
AC Domain	1993	CWRS	5.0	MR	*Lr34*	2.3	R	-
AC Barrie	1994	CWRS	6.5	MS	*Lr13,Lr16*	4.2	MR	-
AC Cadillac	1996	CWRS	7.5	MS	*Lr34*	1.5	VR	*Yr 18*
AC Elsa	1996	CWRS	6.5	MS	*Lr34*	1.3	VR	*Yr 18*
McKenzie	1997	CWRS	3.5	R	*Lr21*	3.8	R	-
AC Splendor	1997	CWRS	7.5	MS	-	3.4	R	-
AC Intrepid	1997	CWRS	3.5	R	-	1.3	VR	-
Prodigy	1998	CWRS	6.0	MS	-	3.8	R	-
AC Abbey	1998	CWRS	6.5	MS	-	2.3	R	-
5600HR	1999	CWRS	4.5	MR	*Lr22a*	7.1	MS	-
CDC Bounty	1999	CWRS	7.5	MS	-	1.9	R	-
5500HR	2000	CWRS	4.5	R	*Lr22a*	7.8	MS	-
AC Superb	2001	CWRS	5.5	R	-	6.9	MS	-
5601HR	2001	CWRS	4.5	R	-	6.6	MS	-
CDC Imagine	2002	CWRS	7.5	MS	-	6.5	MS	*Yr 18*
Journey	2002	CWRS	6.5	MS	-	5.3	MR	-
Lovitt	2002	CWRS	4.5	MR	*Lr21*	4.5	MR	-
CDC Go	2003	CWRS	5.5	MR	-	5.3	MR	-
CDC Osler	2003	CWRS	4.0	MR	-	4.9	MR	*Yr18*
PT 559	2003	CWRS	2.5	R	-	2.9	R	-
5602HR	2004	CWRS	1.5	VR	-	5.1	R	*Yr 18*
Infinity	2004	CWRS	6.0	MS	-	4.6	R	-
CDC Alsask	2004	CWRS	2.0	R	*Lr21*	2.4	R	*Yr 18*
Harvest	2004	CWRS	5.0	MR	-	2.1	R	-
Lillian	2004	CWRS	7.5	MS	-	1.5	VR	*Yr 18, Yr 36*
Somerset	2005	CWRS	2.5	R	-	2.9	R	*Yr 36*
Helios	2006	CWRS	5.5	MR	-	5.3	MR	-
CDC Abound	2006	CWRS	5.5	MR	-	4.2	MR	-

Cultivar	Year of release	Class	Leaf rust (LSM)	Rating (Lr)	Gene(s) Lr	Yellow rust (LSM)	Rating (Yr)	Gene(s) Yr
Alvena	2006	CWRS	7.5	MS	-	2.4	R	-
GoodeveVB	2007	CWRS	4.0	MR	-	5.1	MR	-
Fieldstar VB	2007	CWRS	2.5	R	-	4.1	MR	-
Unity VB	2007	CWRS	3.0	R	-	4.0	MR	-
Waskada	2007	CWRS	2.5	R	-	2.8	R	-
5603HR	2008	CWRS	3.5	R	-	4.2	MR	-
859CL	2008	CWRS	2.5	R	-	3.5	R	-
Stettler	2008	CWRS	4.5	MR	-	2.1	R	-
CDC Kernen	2009	CWRS	6.0	MS	-	6.4	MS	*Yr 18*
CDC Thrive	2009	CWRS	8.5	S	-	6.3	MS	-
CDC Utmost	2009	CWRS	8.5	S	-	5.6	MR	*Yr 18*
CDC Stanley	2009	CWRS	2.5	R	-	5.3	MR	*Yr 17*
Muchmore	2009	CWRS	2.5	R	-	4.8	MR	*Yr 18*
5604HR CL	2009	CWRS	3.0	R	-	4.5	MR	-
Glenn	2009	CWRS	2.0	R	-	4.3	MR	*Yr 18*
Shaw	2009	CWRS	5.5	MR	-	3.8	R	-
Carberry	2009	CWRS	1.5	VR	-	1.9	VR	*Yr 18*
Vesper	2010	CWRS	3.5	R	-	7.3	MS	-
BW423	2010	CWRS	6.5	MS	-	3.8	R	-
PT580	2011	CWRS	3.0	R	-	2.0	R	-
Kyle	1984	CWAD	1.5	VR	-	2.1	R	-
AC Morse	1996	CWAD	1.5	VR	-	1.1	VR	-
AC Avonlea	1997	CWAD	0.5	VR	-	1.1	VR	-
AC Navigator	1999	CWAD	1.5	VR	-	1.5	VR	-
Napolean	2001	CWAD	1.0	VR	-	0.9	VR	-
Strongfield	2004	CWAD	2.0	R	-	3.5	R	-
Commander	2004	CWAD	1.5	VR	-	2.2	R	-
CDC Verona	2008	CWAD	2.0	R	-	5.9	MR	-
Eurostar	2008	CWAD	2.0	R	-	4.7	MR	-
Brigade	2008	CWAD	1.0	VR	-	2.4	R	-
Enterprise	2009	CWAD	1.0	VR	-	4.1	MR	-
Transcend	2010	CWAD	2.0	R	-	4.4	MR	-
DT780	.	CWAD	3.5	R	-	3.0	R	-
DT570	.	CWAD	1.0	VR	-	2.4	R	-
AC Taber	1991	CPS	8.5	S	*Lr14a,Lr13,LrTB*	4.1	MR	-
AC Foremost	1995	CPS	7.5	MS	-	4.3	MR	-
AC Crystal	1996	CPS	6.0	MS	-	4.1	MR	-
AC Vista	1996	CPS	6.0	MS	-	3.6	R	-
5700PR	2000	CPS	3.5	R	-	5.4	MR	-
5701PR	2001	CPS	3.0	R	-	1.7	VR	*Yr 18*
5702PR	2007	CPS	4.5	MR	-	4.1	MR	*Yr 18*
HY682	2009	CPS	8.5	S	-	1.9	VR	-
SY985	2010	CPS	4.0	MR	-	5.0	MR	-
Glenlea	1972	CWES	7.0	MS	*Lr1, Lr13,Lr34*	3.6	R	*Yr 18*
CDC Rama	2001	CWES	7.5	MS	-	1.6	VR	*Yr 18*
CDC Walrus	2003	CWES	8.0	S	-	4.6	MR	-
Burnside	2004	CWES	4.0	MR	-	2.1	R	*Yr 18, Yr 36*
Glencross VB	2007	CWES	6.0	MS	-	4.7	MR	-

Cultivar	Year of release	Class	Leaf rust (LSM)	Rating (Lr)	Gene(s) Lr	Yellow rust (LSM)	Rating (Yr)	Gene(s) Yr
CDC Bison	2008	CWES	6.5	MS	-	6.0	S	-
AC Reed	1991	CWSWS	7.5	MS	-	4.0	MR	-
AC Andrew	2000	CWSWS	8.5	S	-	2.5	R	-
Bhishaj	2003	CWSWS	7.5	MS	-	2.4	R	-
Sadash	2007	CWSWS	6.0	MS	-	1.6	VR	-
Minnedosa	2008	CWGP	5.0	MR	-	2.0	R	-
NRG010	2009	CWGP	3.0	R	-	4.6	MR	-
NRG003	2009	CWGP	7.0	MS	-	3.4	R	-
Snowbird	2000	CWHWS	4.0	MR	-	2.3	R	*Yr 18*
Snowstar	2006	CWHWS	6.0	MS	-	6.2	MS	-

(McCallum and DePauw 2008; Randhawa et al. 2012)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58
56
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1925
1950
1975
2000
YOR
Fit
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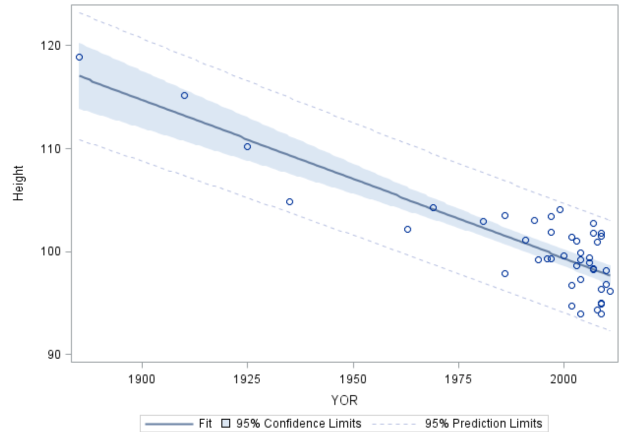
95% Prediction Limits

a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1950
1975
2000
YOR
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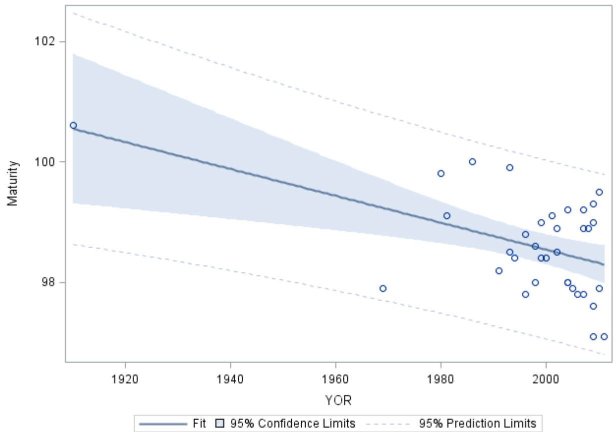
95% Confidence Limits
95% Prediction Limits

b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1940
1960
1980
2000
YOR
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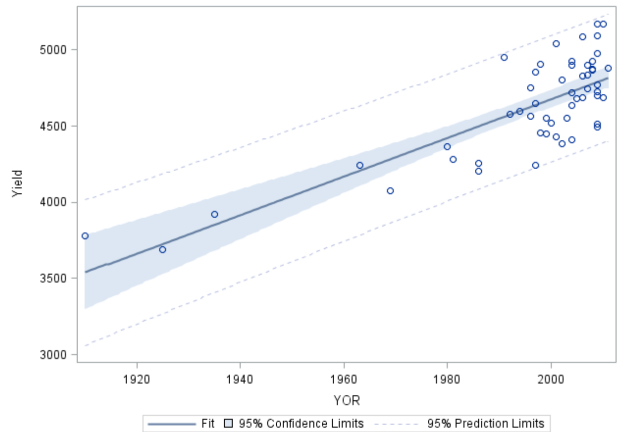
c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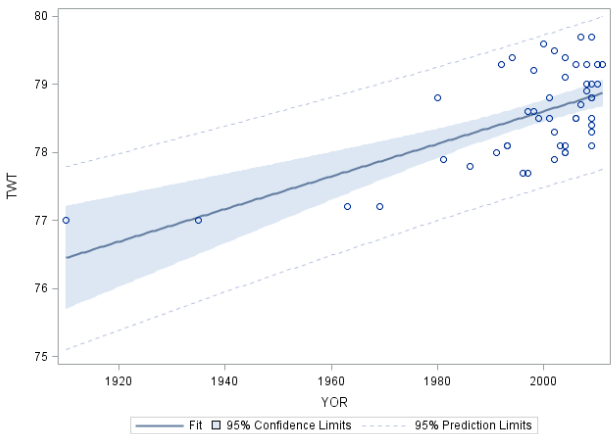
95% Prediction Limits

d



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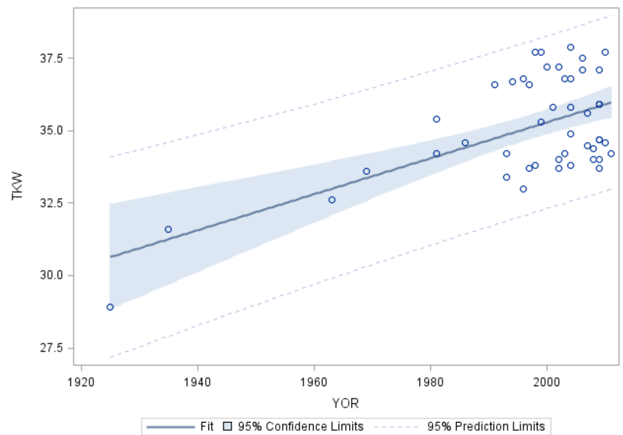

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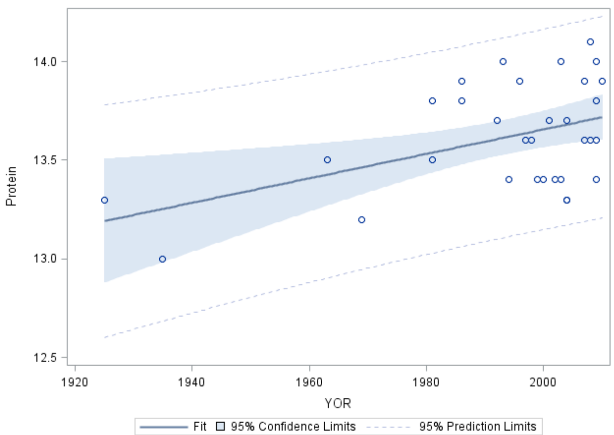
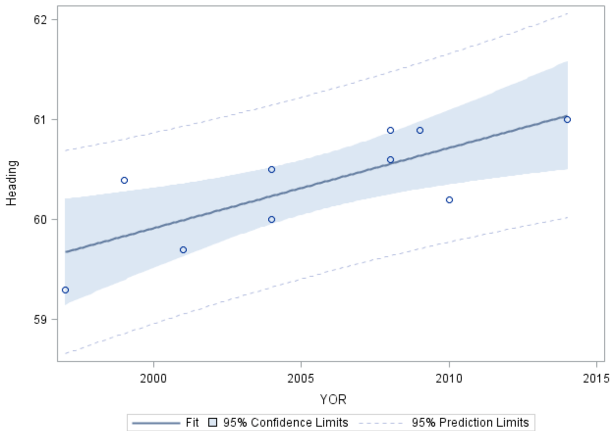


g

Figure 3-1. Regression lines of seven traits versus year of release in the CWRS class. (a): days to heading, (b): height, (c): days to maturity, (d): yield, (e): test weight, (f): thousand kernel weight, (g): protein content.


Heading
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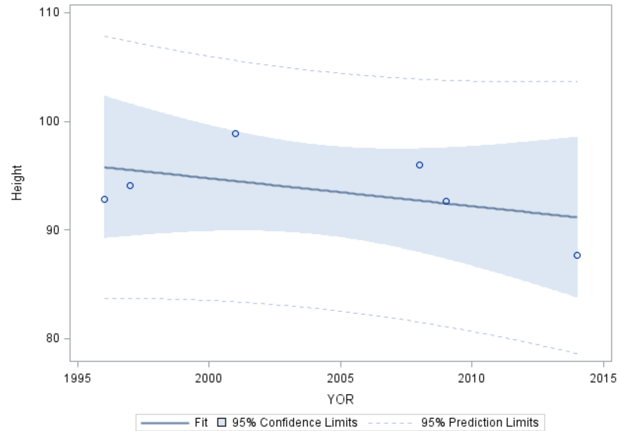
61
60
59
2000
2005
2010
2015
YOR
Fit
95% Confidence Limits
95% Prediction Limits

a


Height
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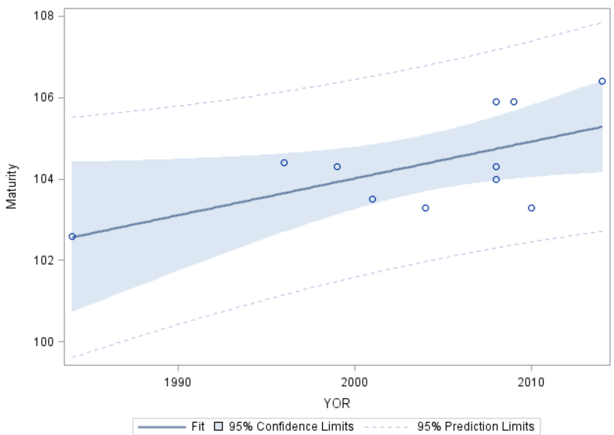
100
90
80
1995
2000
2005
2010
2015
YOR
Fit
95% Confidence Limits
95% Prediction Limits

b


Maturity
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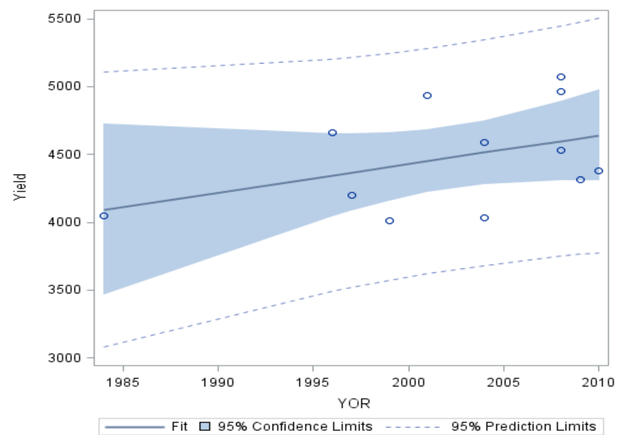
106
104
102
100
1990
2000
2010
YOR
Fit
95% Confidence Limits
95% Prediction Limits

c


Yield
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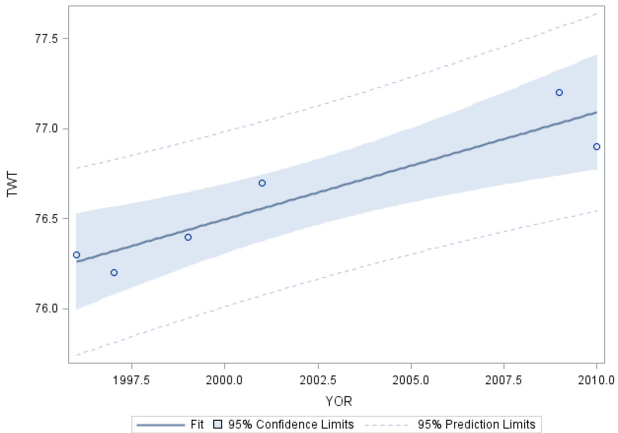
4500
4000
3500
3000
1985
1990
1995
2000
2005
2010
YOR
Fit
95% Confidence Limits
95% Prediction Limits

d



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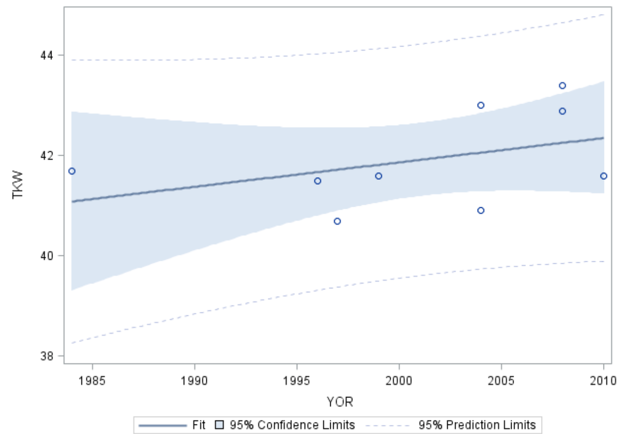

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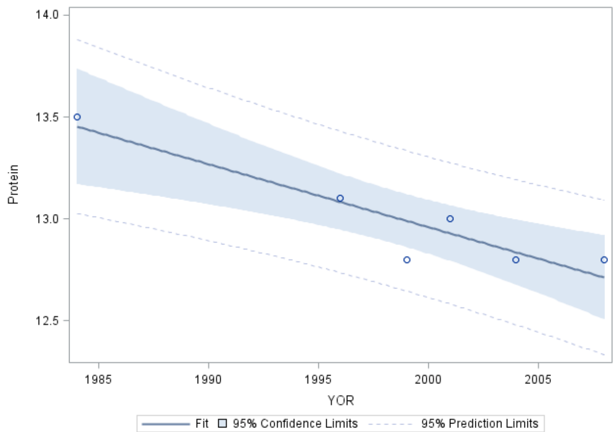
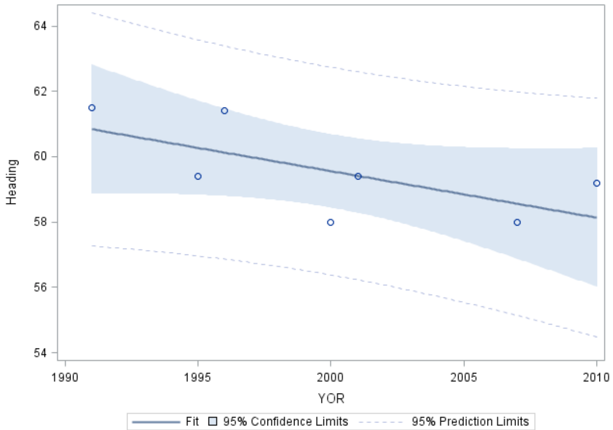
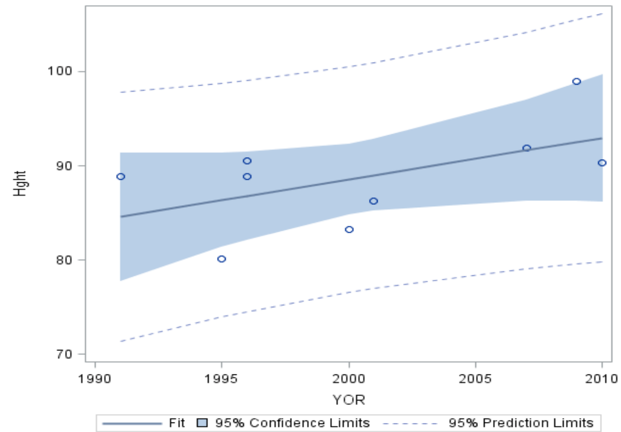


g

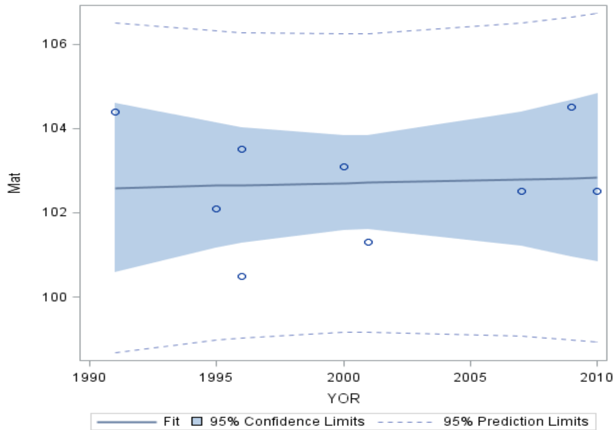
Figure 3-2. Regression lines of seven traits versus year of release in the CWAD class. (a): days to heading, (b): height, (c): days to maturity, (d): yield, (e): test weight, (f): thousand kernel weight, (g): protein content.


Heading
64
62
60
58
56
54
1990
1995
2000
2005
2010
YOR
Fit
95% Confidence Limits
95% Prediction Limits

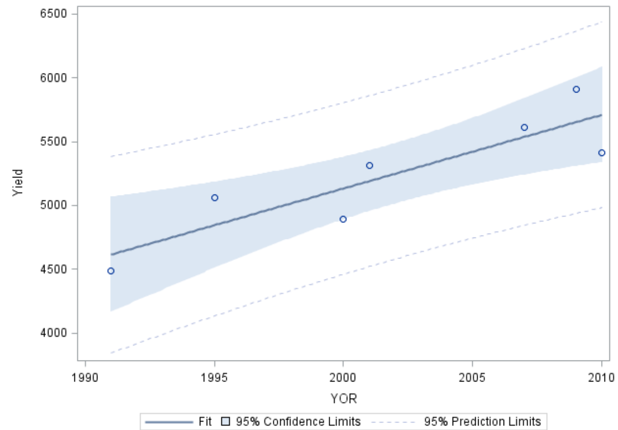
a


Hght
100
90
80
70
1990
1995
2000
2005
2010
YOR
Fit
95% Confidence Limits
95% Prediction Limits

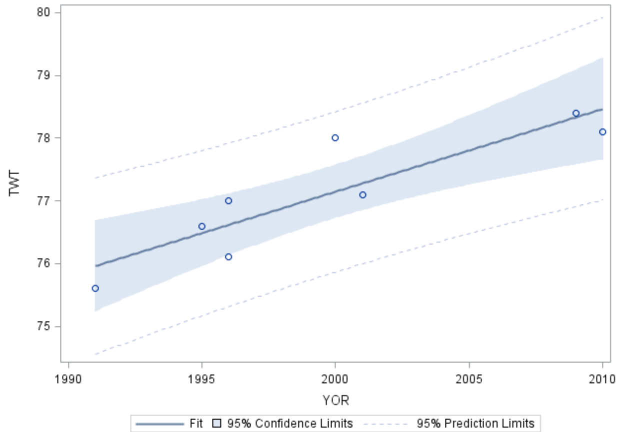
b


Mat
106
104
102
100
1990
1995
2000
2005
2010
YOR
Fit
95% Confidence Limits
95% Prediction Limits

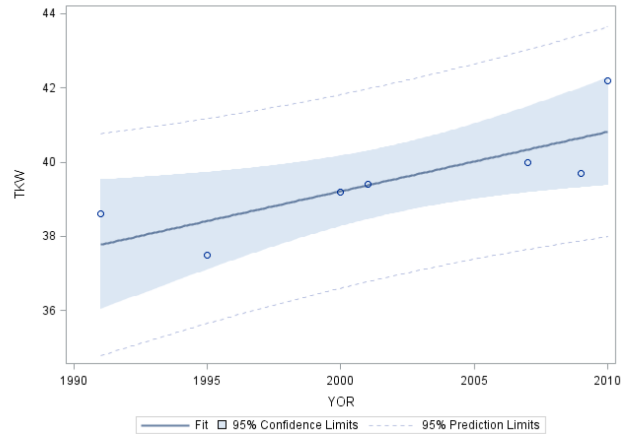
c


Yield
6500
6000
5500
5000
4500
4000
1990
1995
2000
2005
2010
YOR
Fit
95% Confidence Limits
95% Prediction Limits

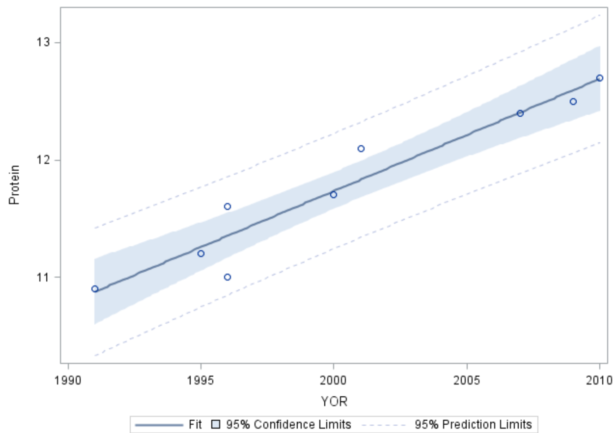
d



e



f



g

Figure 3-3. Regression lines of seven traits versus year of release in the CPS class. (a): days to heading, (b): height, (c): days to maturity, (d): yield, (e): test weight, (f): thousand kernel weight, (g): protein content.