The Performance of Spring Wheat (*Triticum aestivum* L.) Cultivar Mixtures in Conventionally and Organically Managed Systems in Western Canada

by

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Abstract

Wheat cultivar mixtures may positively alter grain yield, quality, improve biotic and abiotic management, and may be employed in both conventional and organic management systems. Such promising benefits have not been thoroughly studied in Canada, especially in the western region where most Canadian wheat is produced. We conducted a twelve site-year study on both conventionally and organically managed locations across western Canada, comparing the performance regarding grain yield, quality, lodging resistance, and weeds suppression of five sole Canadian Western Red Spring wheat cultivars with twenty two-way and three-way mixtures. Mixing Glenn, CDC Titanium, and Lillian produced stable and high yield over a wide range of environments. A three-way mixture of Go Early (tall), Carberry (semi-dwarf), and Lillian (medium height) diminished lodging, leading to improved yield under conventional environments in North Central Alberta and Central Saskatchewan. The two-way mixture of Glenn and Lillian boosted yield in conventional environments in Northwest Alberta and Central Saskatchewan and an organic environment in North Central Alberta. Mixtures managed organically did combine high productivity and elevated grain protein. Mixing lodging-resistant with susceptible cultivars reduced the overall damage in conventional environments. Meanwhile, high-tillering and early heading cultivars are recommended for mixing to retain grain production under weedy environments. In conclusion, wheat cultivar mixtures provided western conventional farmers yield benefits in the presence of abiotic pressures, and organic farmers simultaneous yield and quality benefit.

Preface

I joined wheat breeding and organic farming research group from 2016 to 2017. My experiment was designed by Dr. Muhammad Iqbal and managed agronomically by Klaus Strenzke, Russell Puk, and Joseph Moss. During this time, I was partially responsible for collecting the agronomic data and lodging rate on the field with the guidance of Klaus Strenzke, Hua Chen, Izabela Ciechanowska, Fabiana Dias and the assistance from Katherine Chabot, Russell Puk, Tom Keady, Lindsay Jessup, Brianna White, Joseph Moss, and Rongrong Xiang at Edmonton Research Station, South Campus, University of Alberta and a certified organic farm in Lamont. In 2016, Klaus and Hua Chen evaluated stripe rust, while Izabela Ciechanowska examined leaf spot and common bunt at disease nursery plot. In 2017, I was in charge of evaluating leaf rust, while Izabela Ciechanowska examined leaf spot and common bunt. I also received the recommendation from Amy Kaut (a previous graduate student) and Hiroshi Kubota in data collection.

My experiment was also replicated at Beaverlodge Research Farm in Northwest Alberta, Lethbridge Development Centre in South Alberta, and Kernen Crop Research Farm at the University of Saskatchewan in Central Saskatchewan. At Beaverlodge Research Farm, Greg Semach and Jeremy Hodges were responsible for collecting data on plant height, maturity, lodging rate, and yield. At Lethbridge Development and Research Centre, Dr.Brian Beres and Ryan Dyck were in charge of collecting plant height, maturity, and yield. At Kernen Crop Research Farm, Dr. Pierre Hucl and Mike Grieman were in charge of collecting plant height, maturity, and yield. After the growing season, samples were sent back to the Cereal Quality Lab at the Edmonton Research Station for quality testing

At Edmonton Research Station and certified organic farm, grains were harvested by wheat breeding and organic farming research group. I was responsible for collecting yield data, test weight, and thousand kernel weight. Then, I conducted quality tests for samples from all locations at the Cereal Quality Lab with the assistance of Fabiana Dias, Izabela Ciechanowska in equipment and chemical preparation. After data collection, I was guided by Drs. Dean Spaner, Muhammad Iqbal, and Hua Chen in data analysis. I was in charge of writing my literature review with the numerous recommendations and feedback from Drs. Dean Spaner and Muhammad Iqbal. My research chapter was edited extensively by Drs. Dean Spaner, Muhammad Iqbal, Hua Chen, and graduate student Darcy Bemister with constructive comments and feedback.

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A thankfulness to the volunteer team of the Green and Gold Community Garden of the University of Alberta for embracing me as a little piece of the whole puzzle, offering me unlimited opportunities to learn organic practices, enhance my confidence, and contribute to Edmonton local food and social welfare for African women.

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1.0 Abstract

Wheat has been the principal staple crop since the dawn of human civilization, serving nearly half of the global population. Following the Green Revolution in the 1960s, the agricultural system has been highly modified to optimize wheat development and subsequently maximize production. Yet, that conventional agriculture has been a leading cause of negative impacts on human health, wildlife, and the surrounding environment due to the enormous utilization of agrochemicals in curbing natural and physical limitations. Organic agriculture has arisen as a more sustainable approach than its counterpart, offering numerous advantages regarding social, economic, and environmental implications. Nonetheless, weed infestation, low nutrient availability, diseases have been the key constraints preventing organic producers from achieving high yield. Cultivar mixtures have been appraised as a tactical approach in imitating the ecosystem arrangement through diversifying cultivars of a species. The prospective benefits of cultivar mixtures comprise yield stabilization and improvement, quality enhancement, biotic and abiotic stress management. Combining wheat cultivars attempts to exploit those potential gains and expected to target both conventional and organic agriculture.

1.1 Introduction:

The emergence of agriculture has enabled humans to occupy the world's landscape for thousands of years. The advancement of agronomic practices has accommodated the ever-increasing population over time. Since the last century, rapid population growth has resulted in the application of science in an attempt to alleviate food insecurity. Conventional agriculture, the outcome of that effort, has possibly produced massive quantities of food on less land use and with less manual labor. Coupled with this accomplishment are the unexpected side effects of environmental pollution (Altieri 1998; Horrigan et al. 2002; Pfeiffer 2009), detrimental effects on human health (Thu 1998; Horrigan et al. 2002; Altieri and Nicholls 2012) and other living creatures (Fry 1995; Goulson et al. 2015) through the widespread application of synthetic chemicals, heavy machinery, and luxury irrigation. Organic agriculture has been considered as a more environmentally friendly approach, promoting and enhancing agroecosystem health, biodiversity, biological cycles, and soil activity through the application of agronomic, biological and mechanical techniques instead of synthetic materials (e.g synthetic fertilizers, pesticides, and growth regulators). Some believe that organic agriculture could accustom to the expanding population trend without compromising the ecosystem soundness (McIntyre 2009). Nevertheless, weed aggressiveness, low yield performance, lack of available nutrients, high land requirements, high required energy have been confirmed as the main constraints under organically managed systems (Higginbotham et al. 2000; Finckh et al. 2006; Mäder et al. 2007; De Ponti et al. 2012; Tuomisto et al. 2012).

Cultivated all over the world, wheat covers more of the earth's surface than other staple grain crops (e.g rice, maize, soybean) (OECD 2018). Wheat has been the main source of calories and protein for human consumption for 10,000 years (Pocketbook 2015). More food production including wheat is required to feed the growing population in the coming decades (Cleland 2013). To attain such a goal, a single high-yielding wheat genotype has been commonly cultivated under the most fitting environment. However, the vulnerability of that monoculture practice to diseases, pests, weeds, and climate change is evident (Wolfe and Schwarzbach 1978; Finckh and Wolfe 2006; Machado 2009). Facing those challenges, conventional agriculture has employed agrochemicals and improved agronomic management (Malézieux 2012; Barot et al. 2017). Yet, synthetic fertilizers, pesticides, herbicides, growth regulators are prohibited in organic agriculture (Organic Agriculture Centre of Canada 2009). Thus, overcoming those biotic and abiotic pressures necessitates solutions not relying on synthetic means.

The application of the ecological principle to agricultural systems and practices intends to replace agrochemicals, maintain and increase productivity, and restore ecosystem functions through biodiversity (Borg et al. 2017). That diversification strategy can be executed in two ways, namely species diversity (Loreau et al. 2001) or genetic diversity within species (Hughes et al. 2008). Intercropping which increases the number of species under a given land has been proven to improve productivity but show the complexity of management, especially in mechanized ecosystems (Lithourgidis et al. 2011). Cultivar mixtures, the simplest method to increase within-species heterogeneity, is applicable in mechanized systems, and can sustain, boost yield, and lessen natural and physical stresses in both conventional and organic agriculture (Newton and Swanston 1998; Bowden et al. 2001; Cowger and Weisz 2008; Dai et al. 2012; Costanzo and Bàrberi 2014;

Borg et al. 2017, Ress and Drinkwater 2018). Wheat cultivar mixtures have been gaining attention from scientists, farmers, extension practitioners owing to benefits in controlling various diseases and weeds and pests, reducing inputs, and stabilizing yield (Wolfe and Barret 1980; Zhu et al. 2000; 2005; Vera et al. 2012; Lazzaro et al. 2017). Other potential benefits are grain quality enrichment (Mille et al. 2006; Faraji 2011; Zhou et al. 2014; Lazzaro et al. 2017) and lodging reduction (Murphy et al. 2007; Faraji 2011; Dai et al. 2012).

1.2 Wheat

1.2.1 General Introduction

Three major cereals crops - wheat (*Triticum* spp), rice (*Oryza sativa* L.), and maize (*Zea mays* L) have been the staple food sources for human civilization for more than 10,000 years (Gustafson et al. 2009; Pocketbook 2015). Among them, wheat is the greatest source of calories (Carver, 2009). In addition to human consumption, numerous countries and societies have regarded wheat-based products as cultural and religious symbols (Shewry 2009). Nowadays, wheat continues to occupy a substantial figure in both production and land use, feeding approximately 40% of the world population (Gupta et al. 2005; USDA 2017). Generally, wheat belongs to the family *Gramineae* (*Poaceae*), subfamily *Pooideae*, tribe *Triticeae*, genus *Triticum*. Wheat species are classified based on the number of chromosomes in the vegetative cell, including diploid (14 chromosomes), tetraploid (28 chromosomes), and hexaploid (42 chromosomes) species (Carver, 2009). Currently, two modern wheat species cultivated on a large scale are hexaploid bread wheat (*Triticum aestivum*) and tetraploid durum wheat (*Triticum turgidum spp durum*), used for making macaroni and low-rising bread (Gustafson et al. 2009). A small number of other wheat species (einkorn, emmer, and spelt) are still planted in Spain, Turkey, the Balkans, and the Indian subcontinent (Shewry 2009). A wheat kernel, the edible part, is composed of endosperm (82.5%), bran (15%), and germ (2.5%). The main kernel constituents are carbohydrates, proteins, fatty acids, and a myriad of micro-nutrients such as iron and copper, for example (Kumar et al. 2011). There are also essential amino acids, vitamins, and beneficial phytochemicals found in wheat (Shewry 2009). According to Gupta et al. (1992), wheat proteins are made up of four major proteins, namely prolamines, albumins, gliadins, and glutenins, determining wheat flour quality. Wheat gluten is composed of gliadins and glutenins, forming unique viscoelastic properties of wheat flour to hold gas bubbles and support loaf formation in the baking process (McFall and Fowler 2009). This leavening capability gives wheat an advantage over other crops in making a wide range of bread, baked products, and processed foods. Wheat is categorized technically by the kernel color (red, amber, and white wheat), texture/hardness (hard, medium, and soft wheat), planting/growing cycles (spring and winter wheat) (Asif et al. 2014).

The history of human development and expansion has been shaped profoundly by wheat evolution and domestication (Gustafson et al. 2009). Wheat evolution consists of polyploid convergence and divergence events from several *Triticum* and *Aegilops* species from *Triticeae* tribe, creating polyploidy species (Gustafson et al. 2009). Afterward, earliest farmers selected those species for their superior characteristics (Shewry 2009). Polyploidy is the presence of more than one genome in the plant cells due to interspecific and intergeneric hybridization of two or more distinct species, resulting in increased genetic diversity and improved adaptability to a wide range of environments (Stebbins 1947; Wendel 2000; Gustafson et al. 2009). For example, bread wheat (*Triticum aestivum* L., 2n=6x=48, AABBDD genome) is the result of the hybridization of a primitive tetraploid (*Triticum turgidum*, 2n=4x=28, AABB genome) and wild diplot wheat (*Triticum tauschii*, 2n=2x=14, DD genome) (Hancock 2004). Durum wheat (*Triticum turgidum* spp durum) is the intergenic hybridization and polyploidization between *Triticum uratu* (2n=2x=14, AA genome) and *Aegilops speltoides* (2n=2x=14, SS genome) (Kubaláková et al. 2005). In the past, the wild and ancient wheat had hulled grains and brittle ears that would separate into spikelets at maturity (Carver, 2009). Subsequently, wheat has been artificially selected for desirable characteristics including non-brittle rachis, lack of hulls, non-shattering, lodging resistance, and later for high yield, excellent quality, biotic and abiotic resistances (Carver 2009). Due to wheat domestication, human civilization was transformed from hunter-gatherer to nomadic lifestyle and then sedentary and centralized farming societies in and around the Fertile Crescent nearly 10,000 years ago (Feldman 2001). A small area within the Fertile Crescent in present-day southeastern Turkey and northern Syria has been recognized as the center of wheat domestication through botanical, genetic, and archaeological evidence (Lev-Yadun et al. 2000). Later, the finding of 8,400-year old hexaploid wheat seeds contained naked (*Triticum aestivum*) and hulled (*Triticum spelta*) wheat in Çatalhöyük, Turkey, suggesting an early transition of hexaploid wheat from the Fertile Crescent to Europe (Bilgic et al. 2016). Wheat reached China via Iran, and Africa via Egypt

(Shewry 2009). Eventually, wheat was introduced into the Americas by Spaniards in Mexico, and the English in New England and Virginia (Matz 1991).

1.2.2 International and Canadian Wheat Production

Wheat has been extensively cultivated in a variety of soils and climates ranging from temperate regions to the high elevations of several tropical/sub-tropical areas (Shewry 2009). The major wheat-producing regions include temperate and Southern Russia, the US Central Plains, Southern Canada, Central and Northern Europe, the Mediterranean Basin, Northern China, India, Argentina, and Australia, making these areas the breadbaskets of the world (Gustafson et al. 2009). Because of the superiority to other key grains in nutritive values (e.g 7% to 22% protein content), wheat is utilized widely for making diverse products such as bread, cakes, pasta, cookies, breakfast cereals, confectionary, thickening agents, custards and sauces in Western countries; and noodles, flatbread, and steamed bread in Asian and Middle Eastern countries (Wrigley et al. 2009; Zohary et al. 2012). Additionally, a small amount of wheat has been used as an ingredient for feeding livestock and industrial purposes such as starch and gluten production (Pomeranz 1988; Gustafson et al. 2009). Wheat by-products have been also tested to construct board products from straw, make sweetener from hydrolysis and chemical conversion to xylitol, or extract ethanol from hydrolysis followed by fermentation, opening additional markets for wheat (Graybosch et al. 2009).

The large scale of production and multiple products have made wheat economically and socially important (Rudd 2009). Along with rice and maize, wheat is one of the most widely used grains for human consumption with the worldwide production of 735, 472, and 970 million t respectively (USDA 2017). In 2016, worldwide wheat production was 760 million t, experiencing an increase of 3.5 % (26.6 million t) from 2015 (FAO 2016). Wheat also accounts for the largest production area with 224 million ha in comparison with 179 and 159 million ha in maize and rice correspondingly (USDA 2017). Since 1950 worldwide wheat grain yield has tripled as the result of the improvement in breeding program efforts such as N-use efficiency, disease resistance, reduced height, elevated harvest index, and higher number of kernel per unit area (Rudd 2009). The introduction of agronomic practices since the Green Revolution in the 1960s such as N application, synthetic pesticides, and irrigation has also contributed to improved yield (Borlaug 2007). In 2016, the European Union ranked top in the total wheat production (144 million t), followed by China (129 million t), India (90 million t), Russia (72 million t), and the USA (63 million t) (USDA 2017). An obvious yield deviation among countries has been attributed to genotype by environment interaction (Zhou et al. 2014). Nevertheless, the growing yield trend is apparent in all wheat-producing countries (Rudd 2009).

Canada is one of the top global producers and exporters of premium quality wheat and Canadian wheat is consumed domestically and in more than 70 countries [Canadian Grain Commission (CGC) 2012]. Total production is 31.7 million t, ranking sixth in the world after EU, China, India, Russia, and USA (USDA 2017). Spring wheat, winter wheat, and durum wheat account for 66.4%, 22.3%, and 11.3% of total production respectively (Statistics Canada 2016). The total area harvested is 9.5 million ha (Gain Report 2016). Canadian wheat yields have increased at an average of 1.4 % per year; this has been attributed to the genetic improvement and advanced agronomic management since the 1990s (Agriculture and Agri-Food Canada 2017). In comparison with other countries, Canada wheat yield gains are low due to moisture limitations in western Canada (especially South Western region), and breeding concentrating on high quality and disease resistance (Mason and Spaner 2006). The vast majority of wheat production is from western Canada (Popper et al. 2006). Indeed, despite cultivation throughout the country, the greatest production areas are found in the three Prairie provinces (Alberta, Saskatchewan, and Manitoba) (Agriculture and Agri-Food Canada 2010). Statistically, Saskatchewan harvests 13 million t, followed by Alberta (8.3 million t) and Manitoba (4.2 million t) (Statistics Canada 2015). Canadian wheat classes are categorized by growing regions such as Canada Eastern and Canada Western. Up to approximately 70 % of wheat production is from Western Canadian wheat classes and the number is expected to increase in the coming years (Agriculture and Agri-Food Canada 2017). Canada Western Red Spring (CWRS) and Canada Western Amber Durum (CWAD) have been the most important classes, yielding up to 15 million t and 5 million t respectively (McFall and Fowler 2009). Especially CWRS is well-recognized for superior milling qualities, baking characteristics, and high protein content, making it the key element for the bread-making industry (McFall and Fowler 2009).

1.3 Organic Agriculture

1.3.1 Introduction

Excessive application of agri-chemicals, intensive tillage, and overhead irrigation systems in conventional agriculture have been the primary causes of polluted water, degraded soil, and contaminated air (Lal 2008). Those natural resources, however, are the backbone of human food security (Zuazo and Pleguezuelo 2009). It has been argued that environmental protection and agricultural production need to be in balance because agricultural lands perform numerous functions for humans and concurrently, in natural ecosystems, for other organisms (Gabriel et al. 2013). Thus, feeding the ever-increasing global population and minimizing the environmental footprint are double challenges for the current food production system (Godfray et al. 2010). Organic agriculture has appeared as a prospective solution for both production and environmental integrity (McIntyre 2009). Principally, organic agriculture is based on four pillars: 1) Health: the heathy soils nourish and foster the well-being of humans and animals, 2) Ecology: the farming systems are based on the living ecosystems and recycling process to fit local conditions, 3) Fairness: stakeholders who get involved in organic agriculture should be treated equally regarding life quality, food sovereignty, and poverty eradication, 4) Care: organic practices should be safe, and ecologically sound for not only current but also generations to come (IFOAM 2008). Practically, synthetic fertilizers, pesticides (herbicides, fungicides, insecticides), sewage sludge, growth regulators are not allowed to improve soil nutrients, reduce diseases, insects, weeds, and regulate plant development; genetically modified crops are also not permitted [Organic Agriculture Centre of Canada (OACC) 2009]. Instead of dependence on synthetic inputs, organic farmers rotate diverse crop species to increase organic matter, nitrogen, phosphorus, and manage diseases and parasites (Abawi and Widmer 2000; De Torres et al. 2013; Wright et al. 2017; Aschi et al. 2017), using animal manure to improve soil quality and enhance microbial diversity (Birkhofer etal. 2008; Edesi et al. 2012), growing cover crops to suppress weed development (Deguchi et al. 2015; Anderson 2015), employing minimum tillage to increase the number of microorganisms and their activity (Sun et al. 2016), using mineral-bearing rocks to supply phosphate and minerals for plants (Shivay et al. 2010; Mihreteab et al. 2016), and using parasitoids and predators to control pests (Fusaro et al. 2016).

Those agronomic practices are rooted deeply in the organic agriculture philosophy, placing the emphasis on the harmony between agricultural systems and nature rather than against it. Briefly, human and livestock well-being connect to long-term soil vitality (Kuepper 2010). Howard (1947) and J.I. Rodale stressed that human health and the chain of soil activities are interdependent (Kristiansen 2006). Those activities involve the participation of bacteria, fungi, earthworms, insects, and a host of other organisms (Kuepper 2010). Living soil organisms are responsible for decomposing organic matter into inorganic components for crop use, assisting crop nutrient uptake, or improving soil physical properties (Watts et al. 2001; Watson et al. 2002). For instance, earthworms facilitate soil formation and nutrient cycling via their casts and help improve soil structure and water regulation via their movement and shelters (Blouin et al. 2013; Hoang et al. 2017). It is reported that earthworm populations were higher in organic fields than in mixed conventional fields (178.6 m^{-2} compared to 97.5 m^{-2}) (Blakemore 2000). Additionally, arbuscular mycorrhizal fungi coat and form a mutualistic relationship with roots of more than 80 % of known plant species (including major grain crops such as wheat, corn, rice, and legumes) (Rillig 2004; Habte 2006). These fungi maximize the absorptive ability of crop root hairs to scavenge for phosphorus and nitrogen and provide barriers against pathogens (Rai 2006). The organic soil was found to favor arbuscular mycorrhizal fungi survival and proliferation (Howard 1947). Also, bacteria such as *Rhizobium* and *Bradyrhizobium* spp. strains can form a symbiotic relationship with the legume root system to fix usable nitrogen while using carbohydrates from the hosts, leaving N residue for the subsequent crops (Zahran 1999). Thus, "feeding the soil" has become organic agriculture mantra which revolves around nourishing the living soil in order to better crop growth and eventually human wellness (Kuepper 2010).

1.3.2 Organic vs Conventional Agriculture

Benefits of organic agriculture over conventional agriculture have been reported in a number of studies, including less overall energy usage through avoiding synthetic nitrogen fertilizers which require high temperature (400-600^{0}C) and high pressures (20-40MPa) during the making process (Lockeretz et al. 1981), less soil erosion by incorporating legume green manure in crop rotation and fewer tillage activities (Reganold et al. 1987), higher soil organic matter through using manure and compost (Tuomisto et al. 2012; Vemourougane 2016), reduced nitrogen and phosphorus leaching to the groundwater (Dalgaard et al. 2002; Knudsen et al. 2006; Tuomisto et al. 2012), greater biodiversity of macrofauna and microfauna populations after using safe pest controls (Vemourougane 2016), improved water-holding capacity as a result of reduced bulk density and improved porosity (Letter et al. 2003; Suja et al. 2012). Meanwhile, conventional agriculture is reliant on external inputs to supply nutrients, while some of these sources are not renewable such as phosphorus and some micronutrients. The fluctuation of future energy may raise N fertilizer prices, restricting farmers' access (De Ponti et al. 2012). The ecological services provided by functional biodiversity are also disrupted by pesticides and fungicides application (e.g biological control and pollination), hence reducing production efficiency (Geiger et al. 2010; Tscharntke et al. 2012).

Negative aspects of organic agriculture such as low yield, low available nitrogen, high land requirement have been investigated (Finckh et al. 2006; Mäder et al. 2007; De Ponti et al. 2012; Tuomisto et al. 2012). For instance, Entz et al. (2001) reported that organic crop yields (cereals, legumes, oilseeds) ranged from 50% to 97% of conventional counterparts in 14 organic farms in western Canada. In Southern Australia, wheat yields were 21-31% lower under organic management (Kitchen et al. 2003). More land would be put into practice to achieve a similar production target as conventional agriculture, predicting widespread deforestation on a large scale to gain more farmland (Kirchmann and Ryan 2004). Organic agriculture depends extensively on organic matter-based fertilizers (manure and compost) which are not readily available (van Bueren et al. 2011). As a result, conventional tillage has been employed to enhance organic matter mineralization into available nutrients (Pekrun et al. 2003). Weed eradication in extensive organic agriculture systems remains dependent on conventional tillage, especially in western Canada (Samuel and Guest 1990; Albrecht 2005; Snyder and Spaner 2010; Dai et al. 2014). Yet, this tillage technique has brought about soil compaction and erosion, disrupting root development and causing runoff (Pekrun et al. 2003). Moreover, three times as much draft energy was needed to produce a ton of wheat grain in organic conditions than integrated conventional condition due to tillage implementation (Higginbotham et al. 2000). Canadian organic farmers have shifted to reduced tillage to minimize the negative effects on the soil (Snyder and Spaner 2010). Nonetheless, those farmers have encountered new risks from biennial and perennial weeds associated with this tillage method (Blackshaw 2005).

1.3.3 Global and Canadian Organic Agriculture

The international history of organic agriculture can be evoked by independent events. Soil degradation in Germany between two World Wars, Dust Bowl in the Great Plains, food safety, food security, and environmental issues caused by the chemical-technical intensification farming have initiated the urgent need for an alternative agriculture system (Lockeretz 2007). Several individuals such as Albert Howard in India, Eve Balfour in UK, Rudolf Steiner in Germany, J.I. Rodale and Rachel Carson in US, and Masanobu Fukuoka in Japan are the outstanding pioneers whose scientific work, practical management, and public education have contributed remarkably to advocate organic agriculture (Forge 2001; Lockeretz 2007). Presently, organic agriculture is on the rise in numerous countries due to public attention, the increase in research, and policy support (De Ponti et al. 2012). Up to 172 countries have joined the organic community since 2014 (Willer and Lernoud 2016). There are 2.3 million organic producers globally with the total land use of 43.7 million ha that accounts for 1% of the global agricultural area, while the market of organic food value was worth 80 billion USD (IFOAM 2015). Australia has the largest organically managed land (17.2 million ha), followed by Argentina (3.1 million ha) and the USA (2.2 million ha) (IFOAM 2015). Most of the demand for organic products come from developed nations such as the USA (35.9 billion USD), Germany (10.5 billion USD), and France (6.8 billion USD), whereas more than three-quarters of the producers originate from developing and transition countries (IFOAM 2015). In fact, the number of organic producers is highest in India (650,000), followed by Uganda (190,552) and Mexico (169,703) (IFOAM 2015). Among arable crops, cereals account for the top organic area of nearly 3.5 million ha worldwide, while wheat occupies the largest share in cereals sector (36%) (IFOAM 2016).

Canadian organic agriculture history is a small chapter of the global organic movement. Canadian Organic Soil Association establishment laid the foundation for Canada organic agriculture movement (Cognition 1995). In the 1970s, numerous organizations emerged throughout six provinces to promote the expansion of organic agriculture (Forge 2004). The Canadian Organic Advisory Board (COAB) was formed with a mission as an advisory board for organic producers, processors, and retailers (L'Hoir et al. 2002). Regulatory bodies have been formed to issue organic certification which helps farmers gain a premium over conventional products and enables customers to identify organic products in the market (Forge 2004). Research in organic agriculture has also been supported since then (Caccia 2000). For example, the

Ecological Agriculture Project program at McGill University became the hot spot for organic knowledge exchange throughout Canada (Hill and MacRae 1992). Since 2010, the Canadian Organic Extension Network has been formed to encourage connections between scientists and farmers (Frick 2012).

Like much of the world, the Canadian organic market has been expanding for the past number of years (Holmes and Macey 2009). The Canadian organic market is worth 3.5 billion CAD and ranks fourth in international market share (COTA 2013a). In 2003, there were 3,100 organic producers that accounted for 1.3 % of total Canadian farmers (Forge 2004). After 8 years, the number of producers increased to 3718 which was 1.8 % of total farmers [Canada Organic Growers (COG) 2015]. From 2001 to 2011, the number of farms throughout Canada decreased by 17%, while organic producers grew 67% [Canada Organic Trade Association (COTA) 2013b]. Three Prairies provinces (Saskatchewan, Alberta, and Manitoba) comprise 40 % of total organic farmers and 59% of the total land (COTA 2016). Among them, Saskatchewan is the largest producer of organic field crops (wheat, oat, barley, and flax) (COTA 2014). Most organic consumers choosing organic products tend to have young families and a university education (COTA 2013b). The most important motives of Canadian organic farmers are the reduced utilization of chemicals (33%), negative impacts of conventional farming on the environment (29%), their own health and safety (27%), and higher profit (9%) (Weymes 1990). Other driving forces are consumer health concerns and a sustainable livelihood (L'Hoir et al. 2002; Holmes and Macey 2009). In Alberta, the organic sector is relatively young as there were 290 organic producers in 2011, a slight increase of 5% over 2010 (COG 2015). Hay and field crops dominate organic production, followed by livestock, fruits and vegetables, and a small number of herbs, spices, and mushrooms (COG 2015). The major concerns of Albertan organic growers are weed management, soil fertility, weather, crop/cultivar selection, pests, and diseases (Degenhardt et al. 2005). Generally, the Canadian organic industry is expected to have a bright future thanks to growing consumer demand and the introduction of new organic regulations which strengthen public trust (Holmes and Macey 2009).

1.4 Wheat in Organic Agriculture

1.4.1 Organic Wheat in Canada

Bread wheat (*Triticum aestivum* L.) is currently the principal certified organic crop in Canada, along with durum wheat and barley. Survey data suggests 43% of cereal production area is from wheat, while hard red spring wheat accounts for nearly 50% of the total wheat sector (COTA 2016). Canada's weather conditions and vast farmland suited for mechanization are desirable for cultivating grains, especially wheat (Holmes and Macey 2009). Thanks to the growing market, the quantity of organic wheat export increased five-fold from 1992 to 2003 (Forge 2004). In Alberta, organic wheat production area was 12,787 ha with hard red spring wheat making up the greatest proportion (approximately 38%) (COTA 2016). The Alberta organic grain market has opportunities for development (L'Hoir et al. 2002). Firstly, there is a strong demand from consumers who are aware of organic products, especially organic bread (Canadian Organic Growers 2014). Secondly, the market structure supports the cooperation between producers and their stakeholders (L'Hoir et al. 2002). Thirdly, the national organic certification enhances the trust of organic customers (L'Hoir et al. 2002; Holmes and Macey 2009). Finally, the niche market will bring high net income to organic producers (Organic Alberta 2016).

A number of studies have been conducted to explore wheat performance under Canada organic systems. For instance, Mason and Spaner (2006) concluded that there was a reduction of 40% spring wheat yield in organic systems compared with conventional counterparts. Another study reported 63 % lower wheat yields under organic management (Mason et al. 2007b). Weed competition and nutrient deficiency are limiting factors contributing to yield decline (Blackshaw 1994; Entz et al. 2001; Kitchen et al. 2003; Tuomisto et al. 2012). Grain quality could counterbalance low yield in organic agriculture as high quality has a premium sometimes resulting in high economic net returns to organic producers (Mason and Spaner 2006). Annett et al. (2007) reported that the whole meal protein of organic grains (16.2%) was higher than that of conventional counterparts (14.9%). In another study, although protein content was similar between two systems, greater dough strength was observed in the organic system (Mason et al. 2007a). Moreover, the positive associations between grain yield and test weight, sodium dodecyl sulfate sedimentation

(SDSS), mixing development time, energy to peak revealed that cultivars could combine high yield and good bread-making quality under low-input environments (Mason et al. 2007a).

Other quality parameters such as peak height and total energy under the graph determining gluten strength were greater in the organically managed system (Nelson et al. 2011). The amount of minerals such as Zn, Fe, Mg, and K were also evaluated to be higher, but Se and Cu were lower in organic wheat grains (Nelson et al. 2011). Sensory evaluation panelists could not discern differences in flavor and aroma between conventional and organic bread; however, they would pay more for organic bread if they were aware of the environmental benefits (Annett et al. 2007). In terms of the interaction between wheat and soil microorganisms under organic management, Kubota et al. (2015) reported that the presence of soil arbuscular mycorrhizal fungi (AMF) in the weedy plots under organic land was positively correlated with grain protein content. Hypothetically, AMF is known for their role in assisting nitrogen and phosphorus uptake (He et al. 2003; Smith and Read 2010). Another study showed that the abundance of two different AMF, *Paraglomous* and *Glomus,* enhanced wheat yield under conventional and organic conditions respectively (Dai et al. 2014).

1.4.2 Agronomic Traits of Organic Wheat

In organically managed environments, without using herbicides, a wheat plant has to compete with annual and perennial weeds for growth-limiting resources such as light, water, space, and nutrients (Mason et al. 2007b). Huel and Hucl (1996) reported that wheat height could have the greatest impact on the competitive ability. A negative correlation between weed biomass and plant height was reported in an organically managed system in Alberta, Canada (Mason et al. 2007b; 2008). Since taller crops could prevent sunlight penetration to weeds under the canopy, consequently intercepting a great percentage of photosynthetically active radiation (PAR) and developing early season dry matter (Champion et al. 1998; Mason and Spaner 2006). Modern cultivars with semi-dwarf genes are more sensitive to weed pressure (Mason et al. 2008). Wicks et al. (1986) reported that a short cultivar also appeared to provide excellent weed control, suggesting other agronomic traits contribute to competitiveness.

Early season vigor (ESV) has been associated with the increased competitive ability (Huel and Hucl 1996). Kaut et al. (2009) concluded that ESV was most strongly associated with wheat yield under low precipitation, low nutrients, and high competition in organic systems. The likely reason is that ESV was negatively correlated with weed biomass, but positively associated with spike m^{-2} and yield in organic trials (Mason et al. 2007b). Tillering capacity is another contributing factor (Hucl 1998). A negative correlation was reported between the number of tillers and weed biomass (Korres and Froud-Williams 2002). However, there was no significant difference in the number of tillers among wheat lines under plots over-seeded with Italian ryegrass although one line had greater tillers than other two lines under weed-free conditions (Worthington et al. 2013). Snyder and Spaner (2010) reported that tillering capacity enhanced competitive ability under medium and low weed pressure but was not correlated with yield in weedy conditions. Genotypes with more horizontal leaf orientation [leaf angle distribution (LAD) is 35^0] were more competitive than those with more upright leaves (Huel and Hucl 1996). Similarly, planophile cultivars (LAD of 55^0) exhibited better weed competition than erectophile (LAD is 75^0) cultivars (Hoad et al. 2005). Penultimate and flag leaf length were positively correlated with an aggressive index which measures competitive ability (Acciaresi et al. 2001). Both phenotypes (angle and leaf length) form the canopy structure to reduce sunlight penetration for weed germination and development. Early heading and maturity was also associated with competitiveness but not consistently (Huel and Hucl 1996; Hucl 1998).

Little attention has been paid to below-ground traits which influence the above-ground agronomic traits. The early development of root system will speed up competition for water and nutrients, enhancing shoot establishment (Kruepl 2006). In addition, the allelochemicals (phenolic acids, hydroxamic acids, and short-chain fatty acids) released from wheat have been reported to suppress weed germination and development. For instance, root and shoot extracts of wheat seedlings inhibited the radical elongation of lettuce (Zuo et al. 2005). Likewise, a group of scientists screened the effectiveness of 453 wheat accessions in suppressing ryegrass germination, reporting the degree of inhibition on the root growth of ryegrass ranged from 23.98 % to 90.91% Wu et al. 2000). Overall, competitive wheat genotypes include tall phenotypes, elevated ESV, early maturity, elevated PAR interception, a substantial number of fertile tillers, high early biomass accumulation, and high amount of allelochemicals (Mason and Spaner 2006; Asif et al. 2014).

1.4.3 Breeding Objectives for Organic Wheat

Although organic agriculture has been expanding, breeding for organic production systems has received little consideration. Indeed, most of the breeding successes over the past 60 years have been carried out under conventional management (Wolfe et al. 2008). That is not the case in organic agriculture where biotic and abiotic stresses are not controlled by synthetic means [Organic Agriculture Centre of Canada (OACC) 2009]. Hence, adapted genotypes may be more important under organic environments (Wolfe et al. 2008). There has been a debate regarding breeding wheat cultivars targeting organic agriculture under organic or conventional management. Murphy et al. (2007) stated that direct selection in organic systems produced higher yield potential than indirect selection. That was attributed to better assimilate partitioning at both anthesis and maturity (Wiebe et al. 2016). Indirect selection under conventionally managed systems would not improve the performance of potential lines under the organically managed environment (Reid et al. 2009). Nonetheless, conventional breeding programs do target traits such as grain yield, flour quality and disease resistance which are also important for organic situations (Pswarayi et al. 2014).

Generally, the objectives of organic wheat breeding include weed competitive capacity, disease resistance, greater nitrogen use efficiency, and better end-used quality (Mason and Spaner 2006; Arterburn et al. 2012). In organic farming, one major obstacle is weeds (Degenhardt et al. 2005). A competitive spring wheat ideotype for western Canada organic management would be tall, ESV, early heading and maturity, and a greater number of spike m^{-2} (Mason et al. 2007b). Cultivars demonstrating allelopathic effects against weeds are also desirable (Wu et al. 2000). In organic breeding, soil-borne diseases (bunts, smuts) are more important than rusts (yellow, leaf and stem rust), powdery mildew, and leaf spot diseases which tend to be more severe in high-input environments and inappropriate crop rotation (Van Bruggen 1995; Wolfe et al. 2008; Löschenberger et al. 2008). In moisture-deficit environments, bunts and smuts were the only investigated diseases (Wolfe et al. 2008). Currently, no seed dressing treatments are available for organic wheat, suggesting that breeding for tolerant or resistant cultivars is important (Asif et al. 2014). Fofana et al. (2008) detected three quantitative trait loci (QTL) associated with common bunt resistance. Likewise, Perez-Lara et al. (2017) reported that 54 and 16 out of 81 CWRS cultivars registered between 1963 and 2011 exhibited resistance and moderate resistance to common bunt respectively. Such cultivars are genetic resources for breeding objectives in the future. Fusarium head blight (caused by *Fusarium graminearum, Fusarium culmorum*, and other *Fusarium* species) is another important disease which has caused yield loss and contaminated grain with mycotoxin, especially deoxynivalenol (Windels 2000; Šíp et al. 2010; McMullen et al. 2012). However, complete resistance has been not known yet (Wolfe et al. 2008). Some studies showed tall cultivars with some distance between the canopy and heads supported Fusarium resistance (Mesterhazy 1995; Hilton et al. 1999).

Nutrient use and uptake efficiency are the next targets of organic breeding (Wolfe et al. 2008; Hawkesford 2014; Kubota et al. 2017). Cultivars possessing an extended root system could improve nitrate uptake in N-limited environments (Cox et al. 1985; Laperche et al. 2006). Furthermore, cultivars maximize the crop ability to capture, partition, and remobilize N from the canopy to the grain are desirable (Hawkesford 2014). After grain yield, grain quality is always crucial (Wolfe et al. 2008). Under conventional systems, the negative relationship between grain yield and protein content has been confirmed, which could be due to environmental factors, source-sink interactions, and the dilution of protein by non-protein compounds (Kibite and Evans 1984; Triboi et al. 2006; Blanco et al. 2012). Organic breeding has aimed to dissociate yield from grain protein so acceptable baking quality could be achieved when yield was low (Wolfe et al. 2008). Nowadays, organic wheat breeding has been exploiting cutting edge and non-transgenic breeding technologies such as genomic selection, marker-assisted selection, and high throughput phenotyping to improve results (Baenziger et al. 2011). Breeding genotypes/cultivars which can be mixed together is expected to be the next paradigm shift in agroecology (Wolfe et al. 2008; Litrico and Violle 2015; Barot et al. 2017).

1. 5 Cultivar Mixtures

1.5.1 Introduction

Modern agriculture has evolved into a simplified and mechanized agroecosystem, with a few improved high-yielding species and cultivars, and a large-scale application of natural resources (water and fossil fuels) along with agri-chemicals (fertilizers, pesticides, and growth regulators). These are all hallmarks of the Green Revolution of the 1960s (Malézieux 2012; Barot et al. 2017). The world population is anticipated to rise to 10 billion by the middle of this century, demanding more food (Cleland 2013). To achieve that urgent demand, our current food production system has produced an abundance of food but also has brought about numerous negative consequences for water resources, soil, atmosphere, wildlife, biodiversity, and human health (Altieri and Nicholls 2012). Monocropping, a widespread practice in modern agriculture, has been used to ease planting, monitoring, harvesting, and processing through crop uniformity (Faraji

2011). It is estimated that 75% of crop biodiversity had been lost between 1900 and 2000 (Commission on Genetic Resources for Food 2010). Weeds, pests, diseases, and climate variability have constrained the performance of homogeneous agroecosystems due to the vulnerability of a single genotype over a few years (Wolfe and Schwarzbach 1978; Finckh and Wolfe 2006; Machado 2009). There is a growing acknowledgement of the importance of biodiversity in agricultural production, food security, and environmental preservation (Thrupp 2000; Baumgärtner and Quaas 2010; Scherr and McNeely 2012). Employing strategies mimicking the natural arrangement can lessen disease outbreak (Finckh et al. 2000; McDonald 2010), bring down external inputs (Brooker et al. 2016), reduce nutrient loss, and take advantage of ecological niches (Koohafkan et al. 2012). Organic agriculture also benefits where dissimilar components could buffer against spatial and temporal variation and maintain yield under weedy competition (Wolfe et al. 2008).

Unlike monocultures where each plant is genetically identical, cultivar mixtures consist of several cultivars expressing distinct characteristics (disease and insect resistance abilities) but sharing sufficient similarities (maturity, height, quality, or grain type) to be grown together (Wolfe 1985; Castro 2001). It is impossible to have a cultivar possessing all the desirable traits due to inherent trade-offs between traits (e.g grain yield and protein content, root systems and above ground traits such as grains and leaves). Mixtures could overcome that barrier via pooling a number cultivars having complementary features (Barot et al. 2017). Hence, the objective of cultivar mixtures is not to breed for phenotypic uniformity (Vandermeer et al. 1998), but to exploit the genotypic diversity that brings about benefits such as yield stabilization and improvement, disease control, compensation effects, and reduced inputs (Newton and Swanston 1998; Bowden et al. 2001; Cowger and Weisz 2008; Dai et al. 2012; Costanzo and Bàrberi 2014; Borg et al. 2017).

1.5.2 Cultivar Mixtures in Practice

Cultivar mixtures have been adopted by small-scale and subsistence farmers (Smithson and Lenne 1996; Sthapit et al. 2008), and is increasingly being employed by some large-scale farmers (Zhou et al. 2014). The implementation of mixtures have been found in numerous countries with a variety of crops, such as Switzerland (wheat and barley), Denmark (barley), Poland (wheat, barley, and legumes), Finland (grass), UK (wheat), China (rice), Columbia (coffee), the United States (wheat, forage cereals, and sugar beet), and Canada (wheat) with the attempt to reduce air-borne diseases and pests, and to improve cold injury protection, yield stability, and quality (Finckh et al. 2000; Mundt 2002a; Finckh and Wolfe 2006; Faraji 2011; Vera et al. 2012). In the former German Democratic Republic, barley cultivar mixtures were grown on up to 94 % of the total production area to control the severe outbreak of powdery mildew, which consequently reduced the excessive fungicide cost (Wolfe and Gacek 2001). As a result, the average incidence of powdery mildew decreased by 80%, and total yield remained high along with improved quality for malting and brewing (Finckh and Wolfe 2006). Wheat cultivar mixtures have been the recent choice of American farmers to lower yield loss caused by leaf diseases (Marten et al. 2015). In China, rice cultivar mixtures diminished blast severity up to 90% on a glutinous cultivar (susceptible) and from 30 to 40% on a non-glutinous cultivar (resistant) (Zhu et al. 2005). Consequently, China experienced a break from using fungicides (Zhu et al. 2000). The planted area of rice cultivar mixtures was reported to expand up to nearly 600,000 ha in China in 2003 (Revilla-Molina et al. 2009). The strategy was also developed in blast-prone rice areas in Viet Nam (Finckh and Wolfe 2006). Mixtures have also been grown for feeding livestock. A study showed a positive relationship between the Shannon diversity index (the index follows either from the addition of cultivars or through cultivar evenness) and feed barley yield in 16 regions in Finland from 1998 to 2009, concluding a higher production when more cultivars were mixed (Himanen et al. 2013).

The main barrier of cultivar mixtures could be unacceptable end-use quality (Bowden et al. 2001; Wolfe and Gacek 2001; Finck 2008; Faraji 2011; Barot et al. 2017). In the 1970s, the adoption of cultivar mixtures of wheat and barley was promising in the UK, but maltsters and millers were reluctant to buy the mixed grains, even though the components might have complementary quality characteristics (Finckh et al. 2000). In the case of barley, possible explanations include increased heterogeneity, verification problems, customer preference, and legislation restrictions (Newton and Swanston 1998). Meanwhile, segregating wheat grains having a high protein to achieve quality premiums will be easily accomplished by growing cultivars separately (Bowden et al. 2001). There would be a slight difference regarding quality if cultivars are from the same class but different in disease, pest resistance, and agronomic traits (Finckh et al. 2000). To overcome farmer resistance, it is recommended to demonstrate the productivity of mixtures (Finckh et al. 2000). Take a three-way wheat mixture as an example when it achieved the world yield record of 13.99 t ha^{-1} in the UK in 1981 (Burdon and Chilvers 1982). The disadvantages in agronomic management should also be taken into consideration (Castro 2001). Firstly, mixing different cultivars together would be time-consuming and costly, especially for farmers lacking the necessary equipment (Castro 2001). Secondly, incompatibility among cultivars may cause harvesting problems when mixing early and late-maturing cultivars (Castro 2001). Another agronomic disadvantage is the difficulty of adjusting management practices to meet the physiological requirements of each cultivar (Bowden et al. 2001; Finckh 2008; Fariji 2011). Finally, farmers are encouraged to repurchase new seeds because mixtures are subject to change due to natural selection, interspecific interaction, and environmental pressure (Costanzo and Bàrberi 2014).

1.5.3 Wheat Cultivar Mixtures

Before the late 19th century, heterogenous wheat landraces were broadly cultivated (Machado 2009). Wheat landraces commonly cultivated under low-input environments could tolerate biotic and abiotic stresses of such environments, and yielded sufficiently (Moghaddam et al. 1997). Afterwards, population growth has demanded wheat ideotype more effectively responsive to agriculture advancements, which has replaced landraces with genetically uniform cultivars. However, consequences have been a narrowing genetic base and the risks of homogeneous ecosystems (Harlan 1992; Machado 2009). The concept of diversifying crop cultivars improves biodiversity (Finckh et al. 2000; McDonald 2010; Koohafkan et al. 2012; Brooker et al. 2016). The practice of intentionally mixing two or more wheat cultivars was originally suggested in hard red spring wheat (*Triticum aestivum* L.) and other cereals to cope with an outbreak of stem rust (*Puccinia graminis* Pers.) and leaf rust (*Puccinia triticina* Erikss.) (Wolfe 1985). Other benefits include yield stability and improvement, grain quality elevation, weed and pest control, and lodging reduction (Sarandon and Sarandon 1995; Bowden et al. 2001; Mille et al. 2006; Pridham et al. 2007; Cowger and Weisz 2008; Mengistu et al. 2010; Dai et al. 2012; Zhou et al. 2014). The relative mixing effects tend to be greater in wheat in comparison with other crops such as barley, rice, or oat (Smithson and Lenne 1996; Kiær et al. 2009). Winter wheat cultivars performed better than spring wheat counterparts in mixtures (Borg et al. 2017).

Since 1958, a two-cultivar wheat mixture called Rodco has been grown commercially in Kansas, making use of the complementation of each cultivar (Shaalan et al. 1966). In that mixture, the first cultivar has weak straw, low gluten, and resists wheat mosaic and wheat streak-mosaic, while the second cultivar shows strong straw, high gluten, and withstood leaf rust and Hessian fly (Shaalan et al. 1966). In 2000-2001, wheat cultivar mixtures still occupied 7% of the total wheat hectares in Kansas state (Bowden et al. 2001). Until 2007, wheat mixtures production area expanded to Washington and Oregon state, USA (Faraji 2011). In Canada, Unity VB (a registered cultivar) is the combination between 90% of Unity cultivar (possessing antibiotic resistance gene Sm1 to wheat midge) and 10% of Waskada cultivar (susceptible) to control wheat midge population (Fox et al. 2010; Vera et al. 2013). All subsequent cultivars possessing this gene are required to be released with a susceptible refuge.

1.5.3.1Wheat Cultivar Mixtures and Disease Control

1.5.3.1.1 The Effectiveness of Wheat Cultivar Mixtures on Disease Control

Genetic uniformity facilitates growing, monitoring, harvesting, and processing (Finckh 2008; Fariji 2011; Mikaberidze et al. 2014). Yet, the widespread use of a single resistant gene will favor the continuous selection of mutant biotypes (Johnson 1961; Wolfe 1973; McDonald and Linde 2002; Finckh 2008). As a result, cultivars having a new immune gene are released repeatedly (Mille et al. 2006). Maintaining functional biodiversity could avoid or alleviate disease outbreaks in cereal production (Finckh et al. 2000, McDonald 2010). Wheat cultivar mixtures are organized similarly to managed diseases by diversifying resistance genes in crop stands and matching those genes with the avirulent genes present in the target pathogen population (Mundt 2002a). Furthermore, the durability of a resistant gene could be maintained in mixtures rather than pure culture (Brown 1995). Since the resistant gene will have less exposure to pathogens, this will slow down the selection of new virulent biotypes (Brown 1995; Mundt 2002a). However, a regular change in mixture composition with newly introduced resistant and high-yielding cultivars is recommended to prevent the selection of a complex race and to maintain yield potential (Wolfe and Barrett 1980; Finckh 2008).

Wheat cultivar mixtures can control various diseases, especially air-borne types (Mahmood et al. 1991; Manthey and Fehrmann 1993; Lannou et al. 1994; Akanda and Mundt 1996; Chong et al. 2009; Zhao et al. 2010; Huang et al. 2011; Ning et al. 2012). For instance, winter and spring wheat cultivar mixtures demonstrated reduction of powdery mildew (caused by *Erysiphe grammis* f. sp. *tritici)* and leaf rust (caused by *Puccinia recondita*) compared to pure stands, especially three-cultivar mixtures including one susceptible and two resistant cultivars. Such a mixture make-up also resulted in powdery mildew symptom reduction of nearly 50% (Manthey and Fehrmann 1993). Including a heritage cultivar (Red Fife) in the mixture was observed to have the lowest incidence of leaf rust under organic management (Pridham 2007). Stripe rust (caused by *Puccinia striiformis*) incidence was reduced from 13 to 97% in winter wheat mixtures (Finckh and Mundt 1992a), or from 23 to 33% in a meta-analysis of 11 studies (Huang et al. 2012). Stem rust (caused by *Puccinia graminis* f. sp. *tritici*) severity was decreased when the proportion of resistant cultivars increased in a two-way wheat mixture (Alexandre et al. 1986).

Monocyclic, non-specialized soil-borne and residue-borne pathogens such as tan spot (caused by *Pyrenophora tritici-repentis*), Septoria tritici blotch (caused by *Mycosphaerella graminicola)* spread by spores/mycelium in the soil or by splash dispersal have been assumed to be less effectively controlled than air-borne diseases (Mundt et al. 1995b; Xu and Ridout 2000; Borg et al. 2017). One reason could be that air-borne diseases tend to produce propagules that move away from the inoculum, while soil-borne diseases can re-infect and saturate the leaf area, leading to autoinfection (in which the donor host plant is also the recipient host plant) (Garrett and Mundt 1999; Cox et al. 2004). It is reported that leaf rust was better controlled than tan spot by two-cultivar wheat mixtures in three of four site-years (Cox et al. 2004). Cowger and Mundt (2002) concluded inconsistent effectiveness of winter wheat mixtures on Septoria tritici blotch over a three-year period. In another finding with Septoria tritici blotch, wheat cultivar mixtures exhibited less success than pure stands in reducing pycnidial leaf area in the three upper leaves (Gigot el al 2013). Wheat mixtures also did not reduce the incidence of whiteheads caused by *Cephalosporium gramineum* (Mundt 2002b). Exceptionally, in some studies, wheat cultivar mixtures diminished tan spot (Cox 2004), eyespot caused by *Pseudocercosporella herpotrichoides* (Mundt et al. 1995b), and spot blotch caused by *Bipolaris sorokiniana* (Sharma and Dubin 1996). That could be attributed to the occurrence of secondary cycles of the pathogen, the degree of host specificity, the spatial pattern of the pathogen in the soil (Mundt 2002a), and compensation provided by resistant plants (Wolfe 1985).

Few studies have been conducted on viral diseases due to complex mechanisms (Power 1991), and the abundance and behavior of vector (Mundt 2002a). It was found that the percentage of infected plants caused by the the soil-borne wheat mosaic virus was reduced 32 % and 40 % in a 1:1 and 1:3 mixture (a susceptible and resistant cultivar) respectively compared to the susceptible cultivar in pure stands (Hariri et al. 2001). They assumed that the insufficient primary inoculum and unfavorable conditions for the pathogen might decrease the number of infected plants. In addition, root development, root exudate, thermosensitivity of the resistant cultivar could contribute to lessening virus transmission among susceptible plants (Hariri et al. 2001).

1.5.3.1.2 Mechanisms of Wheat Cultivar Mixtures on Disease Control

Four mechanisms can contribute to disease suppression: 1) dilution effect of susceptible plants, 2) barrier effect of resistant plants, 3) induced resistance of non-pathogenic spores on non-host plants, and 4) microclimate modification (Barret 1980; Burdon and Chilvers 1982; Wolfe 1985; Finckh et al. 2000; Castro 2001; Finckh 2008; Mikaberidze et al. 2014). Firstly, the dilution effect will increase the distance between susceptible plants, which has been concluded as the most important contributor to disease reduction (Wolfe 1985; Burdon and Chilvers 1997; Finckh 2008). Secondly, resistant plants provide barriers preventing spores from infecting other susceptible plants (Wolfe 1985; Finckh 2008; Huang et al. 2011; Mikaberidze et al. 2014). Thirdly, induced resistance caused by avirulent spores activates the biochemical host defenses, slowing down the infection process of the virulent race on the normally susceptible host (Castro 2001; Lannou et al. 2005; Finck 2008). That could account for a third of total disease reduction (Calonnec el al. 1996). Using a computerized model, induced resistance and barrier effect resulted in a decline of virulent spores deposited from the inoculum in grain crop mixtures (Lannou et al. 1995). Finally, differences in component characteristics such as height, canopy traits can modify the surrounding microclimate to be less beneficial for disease development (Castro 2001; Zhu 2005; Pridham et al. 2007; Finckh 2008).

1.5.3.1.3 Factors Affecting the Effectiveness of Wheat Cultivar Mixtures on Disease Control

Smithson and Lenné (1996) reported that disease reduction on wheat cultivar mixtures ranged from 4 to 89%. Several factors influence the efficacy of disease control. Genotype unit area, gradient dispersal, ultimate lesion size, land size, and mixture composition have been studied to affect disease management efficiency (Mundt and Leonard 1986; Garrett and Mundt 1999; Mundt 2002a; Cowger and Weisz 2008). Genotype unit area (GUA) is the contiguous ground area occupied by a given cultivar (Mundt and Browning 1985). Generally, the effectiveness of mixtures will decrease when GUA increases (Mundt 1989; Xu and Ridout 2000). Wheat cultivar mixtures having a random arrangement and alternating rows (low GUA) reduced stripe rust from 15 to 82% in comparison with the mean of sole crops, while alternating swaths (larger GUA) could not control leaf and stem rust (Brophy and Mundt 1991). Secondly, the interaction of GUA with the pathogen gradient dispersal affects the effectiveness of mixtures (Mundt and Leonard 1986). A shallow gradient dispersal results in more inoculum landing on other non-host plants and more spores lost during dispersal due to dilution and barrier effects, whereas a steep gradient dispersal leads to a high degree of autoinfection which tends to reduce mixing effect (Mundt 2002a). Thus, wheat cultivar mixtures have shown greater effectiveness in controlling wind-dispersed/air-borne pathogens (having shallow gradient dispersal) than splash-dispersed/soil-borne pathogens (having steep gradient dispersal) (Mundt et al. 1995b; Xu and Ridout 2000; Castro 2001; Borg et al. 2017). Lesion size is another factor as the continuous expansion of lesions will increase the rate of autoinfection (Berger et al. 1997). Lannou et al. (1994) stated that stripe rust lesions were approximately 200 times bigger than those of leaf rust, leading to higher disease reduction in leaf rust than stripe rust (40% and 20% respectively).

Plot size also has been reported to be another factor (Mill et al. 2006; Cowger and Weisz 2008). The amount of inoculation in small experimental plots would be higher than that in nature, which could lessen the effectiveness of wheat mixtures (Mundt 2002a). With respect to mixture composition, most studies demonstrate that more components control disease more effectively (Mundt et al. 1995b; Huang et al. 2012; Mikaberidze et al. 2014). The decrease of disease severity was modeled to correspond to an increase in the number of components in wheat cultivar mixtures, especially for race-specific pathogens (Mikaberidze et al. 2014). Including more than two components in cultivar mixtures were more effective for the management of wheat stripe (Mundt et al. 1995b; Huang et al. 2012). There has been variation in the proportion of resistant and susceptible cultivars in mixtures (Mahmood et al. 1991; Akanda and Mundt 1996; Alexander et al. 1986; Zhao et al. 2010). For example, adding one-third or more of moderately resistant cultivars reduced leaf rust (Mahmood et al. 1991). In another study, wheat mixtures provided the highest level of disease control with equivalent ratios between resistant and susceptible cultivars (Akanda and Mundt 1996). Under high disease pressure, stem rust severity was not reduced until the proportion of the resistant cultivar was more than 60% (Alexander et al. 1986), or up to more than 80% of the resistant component against stripe rust (Zhao et al. 2010).

1.5.3.2. Wheat Cultivar Mixtures and Grain Yield

1.5.3.2.1 The Effectiveness of Wheat Cultivar Mixtures on Grain Yield

Cultivar mixtures can use sunlight, water, and soil nutrients more effectively than sole crops due to temporal, spatial, and physiological complementarity/compensation, leading to yield stability (Finckh 2008; Faraji 2011; Costanzo and Bàrberi 2014; Barot et al. 2017). Firstly, the diversity in critical phenotypic stages (heading and maturity time) can play a role in yield stability when the yield loss caused by biotic stresses (diseases, pests, and weeds) and abiotic stresses (infertile soil, heat and water stress, frost) of a cultivar is compensated by others escaping these events (Borg et al. 2017). Results from mixtures of *Arabidopsis thaliana* demonstrated that compensatory interactions enhanced stability under abiotic stresses because the fittest and most plastic genotype counterbalanced the loss caused by less fit genotypes (Creissen et al. 2013). The stronger plants in wheat mixtures compensate for the loss of the weaker ones by having more tillers, bigger spikes, and heavier kernels (Fariji 2011). A study found that soft red winter wheat mixtures exhibited more stable grain yield than their components over six environments in North Carolina, owing to buffering against unpredictable stresses (Wolfe and Gacek 2001; Cowger and Weisz 2008). Similarly, two and three-way wheat mixtures produced more stable grain yield than their pure stands over diverse growing conditions in Northeast China (Zhou et al. 2014). Secondly, the difference in height can contribute to stabilizing yield through a number of ways such as 1) better light interception and reduce evaporation through the wavy canopy structure and 2) improve weed competitive ability (Borg et al. 2017). For instance, a mixture of a semi-dwarf wheat cultivar [having elevated leaf area index (LAI)] with medium-height cultivar (early maturing with low LAI) was the most stable yield (Kaut et al. 2009). That could be attributed to the wavy canopy structure created by these two cultivars, which can intercept radiation, decrease shading effect on the neighboring plants, and reduce inter-specific competition (Biabani 2009; Borg et al. 2017), which. Thirdly, the physiological root traits may foster the complementation/compensation effects, resulting in yield stability. When not irrigated, approximately 75% of winter wheat mixtures used water more productively than their pure stands (Wang et al. 2016). A mixture (1:1) of a modern and heritage wheat cultivar exhibited higher water use efficiency than their components in a moderate-drought year, which the authors attributed to the increased root biomass by 70% and 90% in the deep soil layer (0.6-1m) (Fang et al. 2014). That mixture also reduced water use before stem elongation, resulting in greater soil moisture at the reproductive stage, which is most vulnerable to moisture deficit (Fang et al. 2014). Adu-Gyamfi et al. (2015) concluded that water could be pooled by a deeper-root cultivar and distributed to another lower-root cultivar. Such complementation between cultivars in wheat mixtures plays a key role in imparting yield stability than their pure lines (Wolfe 1985).

In addition to yield stability, wheat cultivar mixtures also increase grain yield (Cowger and Weisz 2008; Kiær et al. 2009; Borg et al. 2017). A three-way wheat mixture showed 1.9 % yield improvement in various natural conditions in Nebraska, US (Mengistu 2010). In another study, wheat cultivar mixtures yield 1.5% higher than pure lines in Washington, USA (Gallandt et al. 2001). In Northeast China, a mean advantage of 0.19 t ha^{-1} was detected in a three-wheat cultivar mixture (Zhou et al. 2014). Under severe biotic and abiotic pressures, this yield advantage would be more obvious (Borg et al. 2017). Yield increases of 5.1% and 5.7 % were observed in winter and spring wheat cultivar mixtures, respectively, in the presence of powdery mildew and leaf rust without fungicide treatment (Manthey and Fehrmann 1993). In another experiment, increased yields in mixtures were 6.2%, 1.7%, 7.1%, and 1.3%, in the presence of wheat stripe rust, eyespot, both diseases and no disease, respectively (Mundt et al. 1995b). Under freezing conditions, three-component winter wheat mixtures yielded considerably higher than their components due to compensation for injuries (Bowden et al. 2001). In organic systems, however, wheat mixtures did not yield more grain than pure stands (Pridham et al. 2007, Kaut et al. 2009). Mixtures with high yield potential should be tested on a larger scale and wider range of natural conditions before commercialization (Cowger and Weisz 2008; Vrtilek et al. 2016).

1.5.3.2.2 Factors Affecting the Effectiveness of Wheat Cultivar Mixtures on Grain Yield

Three factors have been investigated to affect yield potential, namely yielding abilities of each cultivar, the interaction among cultivars, mixture composition and disease interaction (Alexander et al. 1986). Firstly, due to wheat breeding progress, cultivars released since 1981 have a higher yield potential and are generally more responsive to N application than those introduced in the 18^{th} century. These modern cultivars could impose a yield decline on traditional cultivars in mixtures because of intense competition for N availability in the soil (Alexander et al. 1986).

Secondly, inter-specific interaction among cultivars can alter the overall grain yield (Finckh and Mundt 1992b). A resistant wheat cultivar yielded highest when mixing with a low proportion of a susceptible cultivar (1%), while the susceptible wheat cultivar reached the greatest yield with the high percentage of the resistant cultivar (90%) (Alexander et al. 1986). Thus, it is challenging to predict the overall yield of mixtures based on the performance of each component in pure stands (Finckh and Mundt 1992a). Thirdly, mixture composition can alter the dilution effect, barrier effect, induced resistance, modified climate, and eventually yield performance (Barret 1980; Burdon and Chilvers 1982; Wolfe 1985; Finckh et al. 2000; Castro 2001). A four-way wheat mixture was superior to three and two-component mixtures for disease control and yield stability (Mundt 1994). Likewise, four-component wheat mixtures performed better than two-component mixtures and pure stands with respect to disease control and yield improvement (Mille et al. 2006). In a case of severe disease, yield advantage of mixtures was up to 6.2 % in many studies (Borg et al. 2017). However, in another experiment, yield losses were very considerable although wheat mixtures protected the plants from wheat stripe rust, eyespot, and both disease combinations (Mundt et al. 1995b).

1.5.3.3 Wheat Cultivar Mixtures and Grain Quality

Wheat cultivar mixtures have been shown to improve grain protein content (Mille et al. 2006; Lazzaro et al. 2017) and baking quality (Faraji 2011; Zhou et al. 2014), have no changes (Walsh and Noonan 1998; Ning et al. 2012), or reduce quality (Kaut et al. 2009). For instance, protein content increases were 2.9 % and 1.1% in a 4- and 2-cultivar wheat mixture respectively in relation to the pure lines under nitrogen application, which could be due to greater nitrogen uptake efficiency (Mille et al. 2006). A twelve-way wheat mixture (6 bread-making cultivars, 3 biscuit-producing cultivars, and 3 heritage cultivars) was evaluated to have higher whole grain protein content and test weight than its mid-component average (Lazzaro et al. 2017). In contrast, under organic management, 2 two-way wheat mixtures exhibited decreased protein content, perhaps because of the competition for nitrogen by a high-protein cultivar under the low-input environment (Kaut et al. 2009). In some cases, the protein content of wheat mixtures was higher than one cultivar, but not often as high as another cultivar having greatest protein content in pure stands (Jackson and Wennig 1997; Kaut et al. 2009).

Other baking qualities have also been tested. A three-way wheat mixture with equal proportion showed a significant improvement in dough rheological properties, water absorption, flour yield, and Zeleny sedimentation value over a cultivar with good quality (Zhou et al. 2014). In another finding, the highest protein content and water absorption indices were from wheat mixtures, although the differences were insignificant (Faraji 2011). Increased water absorption in wheat cultivar mixtures enables bakers to add more water to the flour and increase product yield and shelf-life, hence offering greater economic values (Lee et al. 2005). In another way, Walsh and Noonan (1998) found no obvious advantage of using spring wheat cultivar mixtures in improving milling and baking quality. No effect of two-way wheat mixtures on crude protein content improvement has been found (Ning et al. 2012). Hence, more studies should be conducted to test the effects of mixtures on baking tests (Zhou et al. 2014).

It is hypothesized that the inverse relationship between grain yield and grain protein content could be solved by implementing wheat cultivar mixtures, revealing a potential approach to compensate for the trade-off between two traits (Dai et al. 2012). A mixture (2:1) of a modern (high-yielding) with old cultivar (low-yielding but high protein) yielded as the former and as high protein content as the latter without using nitrogen fertilizer; nonetheless, this result disappeared under high nitrogen input (Sarandon and Sarandon 1995). In another case, two-way wheat mixtures did not maximize yield and protein simultaneously although they were purposely formulated to complement each other (Dai et al. 2012). There is a suggestion that combining cultivars complementing each other for grain yield and mineral nutrients would result in potentially high-yielding wheat mixtures with enhanced nutritional properties (Ca, Cu, Fe, Mg, Mn, P, Zn) in organic farming systems (Murphy et al. 2007).

1.5.3.4 Wheat Cultivar Mixtures and Pest Control

Unlike pathogens, pests can move over the field without difficulty when crops are no longer resistant (Wolfe 1985; Tooker and Frank 2012). Pesticide application helps reduce the damage caused by pests. Nevertheless, pesticides cause harmful effects on humans, other organisms, and to the environment (Pfeiffer 2009; Altieri and Nicholls 2012; Goulson et al. 2015). In organic farming, those chemicals are not permitted to control pest problems (OACC 2009). Using resistant cultivars (bottom-up effects) and promoting natural predators (top-down effects) are advocated to address pest invasion (Tooker and Frank 2012). Cultivar mixtures are considered as a spatial pattern that can enhance the durability of resistant genes (Willhoit et al. 1992) and create shelter and food for the natural enemy (Wolfe 1985; Landis et al. 2000). Orange wheat midge [*Sitodiplosis mosellana* (Géhin)] has been affirmed as one of the most serious pests in three Prairie provinces since 2007, causing shriveled kernels, subsequent yield loss and reduced end-use quality (Vera et al. 2013). In Canada, cultivar mixtures of 90% resistant and 10 % susceptible wheat cultivars have been used to control orange wheat midge [*Sitodiplosis mosellana* (Géhin)] by protecting the resistant gene *Sm1* (which elevates phenolic compounds to starve larvae to death) since 2010 (Vera et al. 2013). The susceptible cultivars (interspersed refuge) provide food for the avirulent midge strains (having dominant genes) which then mate with the virulent ones (having recessive genes) to produce the avirulent hybrid offspring, thereby reducing the selection of virulent biotypes (Vera et al. 2013). Wheat stem sawfly (*Cephus cinctus* Norton) has emerged as another important pest in the Norther Great Plains, reducing both yield and quality (Cárcamo et al. 2005). Mixing a resistant (solid-stem) and susceptible cultivar (hollow-stem) was evaluated to reduce the infestation of wheat stem sawfly when the pest pressure was low (Beres et al. 2009). Another study showed the potential but inconsistent results in managing wheat stem fly over a 3-year period (Weiss et al. 1990). More components could lower the number of aphids (*Rhopalosiphum padi* L.) compared to pure stands, especially six-way wheat mixtures displayed the lowest aphid population (Shoffner and Tooker 2012). They discovered that volatiles and (Z)-3-hexenyl acetate acting as pheromones (luring carnivorous enemies) were higher in three and six-way mixtures; whereas, monoterpenes (attracting aphids) were greater in monoculture (Shoffner and Tooker 2012).

1.5.3.5 Wheat Cultivar Mixtures and Weed Management

According to Entz et al. (2001), the top five common weeds in Canada Prairies were wild mustard [*Brassica kaber* (DC.) L.C. Wheeler], Canada thistle [*Cirsium arvense* (L.) Scop.], redroot pigweed (*Amaranthus retroflexus* L.), green foxtail [*Setaria viridis* (L.) Beav.], and wild oats (*Avena fatua* L.). Weed infestation causes wheat yield loss and quality degradation (Mason and Spaner 2006; Khan et al. 2012). In conventional farming, the most ubiquitous weed control is applying herbicides. Increasing herbicide-resistant weeds has been recognized (Powles and Howat 1990; Owen and Zelaya 2005; Heap 2014). In a late-summer survey from 2007 to 2011 in three provinces (Alberta, Saskatchewan, Manitoba), wild oat, spiny sowthistle, common chickweed, green foxtail, and cleavers were found resistant to herbicide (Beckie et al. 2013). In organic farming, herbicides are banned to control weed problems (OACC 2009). Cultivar mixtures are recommended to control weeds and reduce inputs, especially herbicides (Liebman and Dyck 1993; Newton and Swanston 1998; Mason and Spaner 2006). The dissimilar resource use patterns of components in mixtures allocate better sunlight, water, nutrients, and preempt the resources for weed development (Liebman and Staver 2001). Mixtures of a semi-dwarf and medium-height wheat cultivar could sustain weed pressure and maintain their yield (Kaut et al. 2009). This could be attributed to height variation of components, creating the canopy structure capturing more and leaving less sunlight for weeds germination and development (Sage 1971). In another study, a twelve-cultivar wheat mixture diminished weed density than other treatments in stem elongation stage (Lazzaro et al. 2017). One six-cultivar and two three-cultivar mixtures also suppressed weed better than their mid-component average (Lazzaro et al. 2017). Nonetheless, mixtures of old and modern wheat cultivars did not reduce weed biomass under organic management (Pridham et al. 2007).

1.5.3.6 Wheat Cultivar Mixtures and Lodging Reduction

Lodging can cause yield loss (up to 50%), delay harvest, increase harvesting and post-harvest cost, and reduce bread-baking quality (Stapper and Fisher 1990; Baker et al. 1998; Berry et al. 2007). Lodging occurs as the result of interaction among plants, soil, and the external forces (wind, rain, hail) (Berry et al. 2003). For example, wind will exert a force bending or breaking the stem (stem lodging) or displacing the root system (root lodging), leading to the reduced translocation of mineral nutrients and carbon for grain filling, increased respiration, reduced carbon assimilation within the crop canopy, and fast chlorosis (Berry and Spink 2012). Rain will wet the soil, reducing the attachment between the root system and the soil (Berry et al. 2003). Lodged plants also are infected by fungal diseases and subsequent development of mycotoxin (Scudamore 2000; Berry and Spink 2012). Genetic improvement through the introduction of dwarfing genes and agronomic managements (plant growth regulators, reducing seeding rate, delaying sowing, reducing and delating nitrogen, and rolling the soil) have reduced lodging risks (Berry and Spink 2012). The implementation of wheat cultivar mixtures for resistance against biotic stresses, especially damaging winds is gaining commercial attention (Dai et al. 2012). Since resistant cultivars can provide susceptible cultivars physical support functioning as windbreaks (Faraji 2011, Murphy et al. 2007), which is defined as a facilitation effect (Adu-Gyamfi et al.

2015). For instance, a 1:1 mixture of a resistant and susceptible wheat cultivar showed intermediate degree of lodging; lodging tolerance reached to that of the resistant cultivar when its proportion doubled the susceptible cultivar (Jackson and Wennig 1997). Mixing a stiff-straw with a desirable but poor-standing wheat cultivar enabled the mixtures to remain standing until harvest (Sammons and Baenziger 1985). A three-cultivar wheat mixture was more resistant than its mid-component average under high rainfall during heading to early anthesis (Zhou et al. 2014). However, Kaut et al. (2009) and Dai et al. (2012) found an insignificant effect of wheat mixtures on lodging resistance in both conventional and organic conditions. In addition to physical factors (wind, rain), natural stresses also cause lodging. In a study, wheat mixtures reduced the level of lodging in comparison with the mean of pure stands when the incidence of eyespot (*Pseudocercosporella herpotrichoides*) was severe (Mundt 2002b).

1.6 Conclusion

A more sustainable agricultural environment where fewer inputs are used to control biotic and abiotic constraints should be promoted. One possible tool could be organic agriculture where cultural, biological, and mechanical means are employed. Some constraints have been recognized under organically managed environment, requiring novel strategies. Wheat cultivar mixtures have significant potential for managing diseases and pests, weeds, and lodging in both conventional and organic production systems. Wheat cultivar mixtures also have been well-proven to stabilize yield better than monoculture and enhance grain yield. Milling and baking quality are promising but further studies demonstrating the consistent value are needed. Wheat cultivar mixtures have been applying in several countries such as USA, UK, Switzerland, Poland, China, Indian. In Canada, wheat cultivar mixtures have been released to manage orange wheat midge, suggesting increasing attention from producers. Canada research in wheat cultivar mixtures is in infancy. More studies are crucial to confirm the effectiveness of cultivar mixtures in Canada, especially western Canada where most wheat is produced.

1.7. Statement of Purpose:

A well-designed study of spring wheat cultivar mixtures conducted in western Canada attempts to uncover the potential benefits for both conventional and organic systems. Conventional farmers could employ mixtures immediately if they could maintain or exhibit better yield performance than monoculture over a wide range of environments. The local adaptability of each mixture is also considered if the interaction between mixtures and environments was positive. Organic farmers could identify competitive mixtures under low-input environments if these mixtures could either remain yield under weedy pressure or suppress weed development. Mixtures would meet the end-use requirement if the milling and baking qualities could be at least comparable to their respective components. Eventually, this study would better understand wheat cultivar mixtures in Canada and contribute other insights to the scientific community in this field. The objectives of this research are:

1. To evaluate the performance of components and wheat cultivar mixtures grown under conventional and organic conditions.

2. To evaluate the grain quality of components and wheat cultivar mixtures grown under conventional and organic conditions.

3. To compare weed suppression of components with wheat cultivar mixtures grown under organic condition.

4. To compare the degree of lodging resistance of components with wheat cultivar mixtures under conventional and organic conditions.

The underlying null hypotheses tested were:

1. The performance of components and wheat cultivar mixtures do not differ under conventional and organic conditions.

2. There are no differences in grain quality of components and wheat cutivar mixtures grown under conventional and organic conditions.

3. Components and their mixtures do not differ in weed suppression under organic condition.

4. Components and their mixtures do not differ in resisting lodging under conventional and organic conditions.

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The performance of spring wheat (*Triticum aestivum* L.) cultivar mixtures in conventionally and organically managed systems in western Canada

2.0 Abstract

The practice of wheat cultivar mixtures has been acknowledged as an ecological approach to stabilize yield, control diseases, and restrain pest invasion in both conventional and organic systems. Other important areas of research such as grain quality, weed management, and abiotic resistance have received less attention in Canada, especially in the prairie provinces. We aimed to compare yield, grain quality, weed suppression, and lodging reduction of wheat cultivar mixtures with their component cultivars in conventional and organic environments. Field trials were arranged in randomized complete blocks in four conventional locations (Edmonton Conventional, Beaverlodge, Lethbridge, and Kernen) and two organic locations (Edmonton Organic and Certified Organic) in Alberta and Saskatchewan, Canada from 2016 to 2017. Five Canada Western Red Spring (CWRS) wheat cultivars (Go Early, Carberry, Glenn, CDC Titanium, and Lillian) were selected for contrasting characteristics in morphology, yield performance, grain quality, disease, insect, and lodging resistance abilities. Two and three cultivars were mixed with equal proportions to compose twenty different two-way and three-way mixtures respectively. We investigated that yield and grain protein decreased in the organic environment, while gluten was stronger in several mixtures. The inverse correlation between grain yield and grain protein was altered by cultivar mixing, and mixtures did not provide weed control better than their respective components in the organic environment. Lodging damage was reduced by mixing susceptible with resistant cultivars in conventional environments. Averaged across locations in western Canada, two mixtures (Glenn-Lillian, Go Early-Glenn-Lillian) yielded considerably greater than their respective components, and the mixture of Glenn, CDC Titanium, and Lillian was desirable for both yield stability and high productivity. Regarding mixing ability effect on yield, CDC Titanium appeared to be the highest yielder and the best mixer, while Lillian was the opposite; the specific combination of Glenn and Lillian was the most compatible across environments. Mixing a weak-gluten cultivar with strong-gluten cultivars was found to improve the overall gluten quality. In conclusion, wheat cultivar mixtures offered yield advantages to conventional farmers in the presence of abiotic stress (e.g strong wind, or heavy rain), and provided a yield benefit and increased quality to organic producers.

2.1 Introduction

Wheat (*Triticum* spp) has been consumed in versatile products (bread, pasta, noodles, cakes, etc), providing carbohydrates, proteins, fatty acids, trace minerals, vitamins, soluble, and insoluble fibers (Kumar et al. 2011; Pocketbook 2015). Most production has come from conventional agriculture, which has contributed substantially to global food security over the past five decades (Foley et al. 2005). However, due to the harmful impacts of conventional agriculture, organic agriculture has emerged as a more environmentally friendly production system (McIntyre 2009; Sandhu et al. 2010; Reganold et al. 2016). Under organically managed systems, a major constraint is weed infestation (Degenhardt et al. 2005; Mason et al. 2007). The success of organic agriculture relies on the availability of highly competitive cultivars. Wheat cultivars expressing agronomic traits such as taller plants, early season vigor, early maturity, elevated photosynthetically active radiation interception, great fertile tillers, and high early biomass accumulation are more competitive than others in weedy environments (Mason and Spaner 2006) because of the intense competition for limited natural resources (Mason et al. 2007). Efficient nitrogen use, disease resistance, and better end-use quality are also desirable traits to cope with low nitrogen availability, no pesticide application, and low yield performance under organic conditions (Mason and Spaner 2006; Arterburn et al. 2012; Kubota et al. 2017). Mixing several cultivars prior to planting is a prospective approach, making use of their synergy against weeds, diseases, and insects for both organic and conventional farming systems (Litrico and Violle 2015; Barot et al. 2017).

The practice mixing cultivars is a strategy to combine the simultaneous cultivation of several cultivars which have dissimilar trait expression (yielding abilities, drought tolerance, disease and insect resistance, etc) but share sufficient resemblance (maturity, height, quality, or grain type) (Wolfe 1985). The unique advantage of mixtures is to have a package of many desirable traits from different cultivars, which is unlikely to be present in one cultivar due to the trade-off between traits (e.g grain yield and protein content) (Barot et al. 2017). Typically, it is common to blend wheat flour from different cultivars after milling to attain quality consistency or fulfill the special customer demand, suggesting the potential of growing wheat cultivar mixtures (Barot et al. 2017). Wheat cultivar mixtures have been investigated broadly for testing mixing effectiveness, which revealed better results than other crops (e.g barley, rice, oat, etc) (Kiær et al. 2009). Most studies have focused on the effectiveness of wheat cultivar mixtures on stabilizing and boosting yield due to complementation, compensation, and facilitation effects (Mahmood et al. 1991; Manthey and Fehrmann 1993; Chong et al. 2009; Zhao et al. 2010; Dai et al. 2012), reducing disease severity due to dilution and barrier effects, induced resistance and climate modification (Lannou et al. 1994; Akanda and Mundt 1996; Cox et al. 2004; Cowger and Mundt 2002; Ning et al. 2012; Gigot et al. 2013), and keeping pest populations under control through employing interspersed refuges (Fox et al. 2010; Vera et al. 2013).

Cultivars in wheat mixtures should be from the same class to retain end-use quality (Jackson and Wennig 1997). Grain quality characteristics such as test weight, protein content, water absorption, Zeleny sedimentation values have been evaluated in wheat cultivar mixtures, showing promising but not consistent results in enhancing these characters (Walsh and Noonan 1998; Mille et al. 2006; Faraji 2011; Ning et al. 2012; Zhou et al. 2014; Lazzaro et al. 2017). Breeding advances have been relatively slow in integrating high grain yield and high grain protein due to their inverse relationship (Kibite and Evans 1984). Hence, it is expected that wheat cultivar mixtures could reverse that relationship through complementarity (Dai et al. 2012; Zhou et al. 2014), especially in low-input environments (Sarandon and Sarandon 1995). Wheat cultivar mixtures have also been found to outcompete weeds. Since mixtures could either create a specific canopy arrangement cutting off sunlight reaching the soil for weed germination and development (Newton and Swanston 1998; Kaut et al. 2009) and/or better utilizing soil nutrients due to the difference in root systems (Liebman and Staver 2001; Adu-Gyamfi et al. 2015). Lodging incidence also decreased in a mixture when a lodging resistant cultivar provided the susceptible cultivar with physical support against strong outer forces (Sammons and Baenziger 1985; Jackson and Wennig 1997). More studies on grain quality, weed suppression, and lodging resistance are necessary to increase the reliability of implementing wheat cultivar mixtures.

Winter wheat has been extensively used for testing the effects of mixtures (Mahmood et al. 1991; Manthey and Fehrmann 1993; Akanda and Mundt 1996; Cox et al. 2004; Mundt 2002; Cowger and Weisz 2008; Gigot et al. 2013), while spring wheat has been less studied (Alexander et al. 1986; Pridham et al. 2007; Dai et al. 2012; Vera et al. 2013). In Canada, up to 66% of total wheat production is from spring wheat (Statistics Canada 2016), and hard red spring wheat accounts for nearly 50% of the total organic wheat production area (COTA 2016). The number of studies on wheat cultivar mixtures conducted in western Canadian environments has been limited (Pridham et al. 2007; Beres et al. 2009; Kaut et al. 2009; Vera et al. 2013; Smith et al. 2014).

Therefore, testing spring wheat mixtures in a wide range of western Canadian environments would greatly benefit both the conventional and organic wheat industry.

In this study, we aimed to: 1) evaluate the performance of CWRS wheat cultivar mixtures in terms of yield, quality parameters, weed suppression, and lodging resistance in both organic and conventional management systems, 2) identify the stability and adaptability of wheat cultivar mixtures across a wide range of natural conditions of western Canada, and 3) determine the agronomic traits which contribute to yield in conventional locations and weed suppression in organic locations. The results are expected to help farmers decide which wheat cultivar mixtures and characteristics to use as a reference for mixing.

2.2 Materials and Methods

Five CWRS wheat cultivars, all registered in western Canada after 2000, were selected based on the difference in morphology (height), yield performance, grain quality, disease and insect resistance, and lodging protection (Table 2.1). The selection of cultivars was carried out without prior knowledge of their performance in mixtures. Go Early is an early maturing cultivar with very good bunt resistance (Alberta Seed Guide 2018). Carberry is a semi-dwarf, high yielding cultivar which is very resistant to lodging (DePauw et al. 2011). Glenn is a strong-stem cultivar which is also very good at resisting lodging with high end-use quality (Mergoum et al. 2006). CDC Titanium is a wheat midge [*Sitodiplosis mosellana* (Géhin)] tolerant cultivar with *Sm1* gene on chromosome 2B (Alberta Seed Guide 2018; Thomas et al. 2005). Lillian is a solid-stemmed cultivar which confers resistance to wheat stem sawfly (*Cephus cinctus* Nort.), with *Gpc-B1* gene (high protein concentration gene) and *Yr36* gene (stripe rust resistant gene) on chromosome 6BS (DePauw et al. 2005; 2007). The five cultivars were used to construct twenty two-way and three-way combinations with equal proportions of each cultivar. Cultivars and mixtures were grown at the same seeding density, and in this study are referred to generically as "entries". Mixtures were prepared each year to ensure the exact proportion of each cultivar. The cultivar 'Park' was grown as a border of each trial. Each experiment at each location was laid out as a randomized complete block with three replications. Each replication contained all twenty five entries (Table 2.1).

In 2016, the trials were conducted at six experimental locations in western Canada [two at the Edmonton Research Station in Edmonton, Alberta, Canada (≈ 53029'N, 113032'W), one at a certified organic farm at Lamont, Canada (≈ 53045'N, 112043'W), one at the Lethbridge Research and Development Centre in Alberta, Canada (≈ 49042'N, 112046'W), one at the Beaverlodge Research Farm in Alberta, Canada (≈ 55012'N, 119024'W), and one at the Kernen Research Farm in Saskatoon, Saskatchewan (≈ 52009'N, 106032'W)] (Figure 2.1). In 2017, the trials were carried out at similar locations, except the trial at Lamont was moved to the Edmonton Research Station. As a result, there were two trials conducted in Edmonton Organic condition in 2017 (planted at different dates). Soil fertility levels of each location (only soils at Edmonton Research Station and Lamont were tested) are presented in Table 2.3. The soils at Edmonton Research Station and Certified Organic Farm are classified as Black Chernozemics, soils at Lethbridge and Kernen are Dark Brown Chernozemics, and soils at Beaverlodge are Dark Gray Luvisols (Saskatchewan Ministry of Agriculture 2009; Alberta Agriculture, Food and Rural Development 2015) (Table 2.4). These locations describe climatologically diverse growing conditions of western Canada. For instance, Edmonton Research Station and Lamont, Lethbridge Research and Development Centre, Beaverlodge Research Farm, Kernen Research Farm represent the typical natural conditions of north central Alberta (continental climate), south Alberta (cold semi-arid), northwest Alberta (humid continental climate), and central Saskatchewan (warm-summer humid continental) respectively.

Fertilizer application, pest control, and seedbed preparation varied across locations and were representative of common practices of each site. Field trials in Edmonton location were fertilized based on Farm Soil Analysis recommendation for a grain yield goal of from 60 bu/ac-80 bu/ac. In 2016, Edmonton Conventional received 70kg ha^{-1} of urea (46-0-0), and N-rich (25-15-15) with seeds, and herbicides (375 mL ha^{-1} of Marengo, 2 L ha^{-1} of Curtail M, and 0.5 v/v % of Turbocharge). At the Edmonton Organic location, no manure or compost was applied due to the relatively high nitrogen level from the previous field pea crop. Hand weeding was necessary when the presence of thistle and dandelion was severe at this location. No external input was applied at the Certified Organic Farm with oat as the preceding crop. All experimental trials followed cultivation. The trial at Kernen Research Farm was fertilized with 50 kg ha^{-1} of NPK (28-23-0) and 1.12 L ha^{-1} of herbicide Velocity. In 2017, Edmonton Conventional was applied with mono-ammonium phosphate (11-52-0). The trial at Kernen Research Station received 50 kg ha^{-1} NPK fertilizer (28-23-0) and 1 L ha^{-1} herbicide Velocity. The trial at Beaverlodge Research Farm was fertilized with 112 kg ha^{-1} of mono-ammonium phosphate (11-52-0), 172 kg ha^{-1} of phosphorus-free fertilizer (24-0-12) and Sulphur.

At Edmonton (both Conventional and Organic), the soil was cultivated in the spring (prior to seeding) and the end of the growing season (fall). An additional tillage was applied to eradicate weeds before seeding at the organic sites. The trial plots at Edmonton and Certified Organic farm were six rows wide (23 cm row spacing) and 4m long, while plots at Kernen were five rows wide (20 cm row spacing) and 3.66 m long. Plots at Beaverlodge were four rows wide (22.86 cm row spacing) and 6m long. An automatic, no-till, double-disk plot seeder (Fabro Enterprises Ltd., Swift Current, SK, Canada) was utilized for seeding in Edmonton in both years. The standard seeding rate was 300 seeds m^{-2} (the difference in kernel weight of each cultivar was adjusted when the seeding rate was determined). Each cultivar would have the number of seeds based on its proportion in the mixture.

2.3 Data collection

Twenty random plants were selected in each plot to measure height from the ground to the top of the spike (excluding the awn) before maturity, then the average was calculated. Time to heading (days) was recorded when 75% of plants in the plot were fully headed (the head completely emerged out of the flag leaf sheath). Time to maturity (days) was recorded when 75% of plants in the plot were physiologically mature (spike and peduncle lose green color). Light interception (LI) was the percentage (%) of sunlight captured by the plant canopy, as recorded by using an LI-191 Line Quantum Sector (LI-COR Environmental, Lincoln, Nebraska) at solar noon in a non-cloudy day as close to June 21st (the longest day of the year) as possible. Before maturity, the number of tillers was counted within a 25 x 25 cm quadrat placed a foot from the front of each plot and between the third and fourth row, converted to the number of tillers per m^2. Lodging assessments were conducted based on the percent of lodged plants after the presence of strong external forces (e.g wind or rain), where 0=0-10%, 1=11-20%, 2=21-30%, 3=31-40%, 4=41-50%, 5=51-60%, 6=61-70%, 7=71-80%, 8=81-90%, 9=91-100%. In Edmonton Organic, above ground (without roots) weed biomass was collected within a 25 x 25 cm quadrat between the second and third row; dried at 45^0C for 72 hours; weighed and converted to biomass per m^2. A Wintersteiger plot combine (model Nurserymaster Elite, Wintersteiger, Austria) was used to harvest at Edmonton Research in both years and Certified Organic in 2016. However, at the Certified Organic farm in 2016, no yield data was collected because early snow caused lodging and grain shattering; however, there were sufficient grains harvested following the snow event for quality evaluation. After harvest, the grain samples were dried for 3 days at a consistent temperature of 45^0C. Pfeuffer sample cleaner (model SLN3, Pfeuffer, Germany) was used to remove chaff, shriveled grains, and weed seeds. Yield data was collected by measuring total seed weight of each plot, converted to t ha^{-1}.

Test weight (TW) was measured by weighing the total seeds in a dry pint (0.5 L), then converted to kg hL^{-1}. Thousand kernel weight (TKW) (g) was determined by doubling the weight of 500 seeds counted by Agriculex ESC-2 Seed Counter (Agriculex, Canada). Protein content (%) was recorded by a Unity 2400 RTW Spectrastar NIR Spectrophotometer (Unity Scientific, USA). Samples were milled using a Cyclone Sample Mill Belt Drive Model 3010-030 (UDY, USA). Hagberg falling number was recorded by Perten Falling Number 1700 Analyzer (Perten, Sweeden) according to AACC Method 56-81.03 to determine the level of enzyme alpha-amylase (the sprouting damage) in the flour, which was the total time (seconds) measured from the fall of the viscometer stirrer down to the prescribed distance through the gelatinized suspension. The activity of enzyme alpha-amylase is high when falling numbers are below 300 (McFall and Fowler 2009). SDS sedimentation value (ml) was recorded according to AACC Method 56-61.02 to test the flour gluten strength as the result of gluten sedimentation volume in a dilute lactic acid solution.

2.4 Data analysis

Analysis of variance (ANOVA) for all traits was conducted using R environment for statistical computing, version 3.3.2 (R Core Team 2016). Field trials were designed as randomized complete blocks with entry was the main treatment at each location. At Edmonton Research Station, the experiment was treated as a split-plot design when management practices (conventional and organic) were taken into consideration in which the management practice was the main plot and entry was the subplot. A comparison of entry performance between conventional and organic environments was conducted using a linear mixed-effects model in 'nlme' package (Pinheiro et al. 2017), in which management practice, entry, and the management by entry interaction were the fixed factors, and year and year by management interaction were the random factors. Least square means were obtained by running the "lsmeans" package (Lenth et al. 2017). Contrasts were performed to compare each mixture and its mid-component average (Table 2.6). The mid-component average of a mixture was the combined average pure stand value weighted by the frequency of components in the mixture. For example:

The mid-component average of two-cultivar mixtures = $Y_{mo1} . P_1 + Y_{mo2} . P_2$

The mid-component average of three-cultivar mixtures = $Y_{mo1} . P_1 + Y_{mo2} . P_2 + Y_{mo3} . P_3$

(Y_{mo1}, Y_{mo2}, Y_{mo3} are the yield of cultivar 1, cultivar 2, and cultivar 3 respectively in monoculture and P_1, P_2, P_3 are the proportion of cultivar 1, cultivar 2, and cultivar 3 respectively in the mixture).

Relative yield (RY) is a useful index to determine when the mixture is more or less productive than expected based on the component cultivars, which was the result of the subtraction of the mid-component average from the actual yield of the mixture when we run contrasts (Reiss and Drinkwater 2018). An RY > 0 indicates a yield benefit from mixing, an RY < 0 indicates a yield penalty from mixing, and an RY = 0 indicates no change in yield from mixing compared to the component cultivar yields.

ANOVA for all traits was carried out for Certified Organic, Beaverlodge, Lethbridge, and Kernen separately; where we performed the linear mixed-effects model in R environment (Pinheiro et al. 2017) in which entry was the fixed factor, year and replication nested within year were treated as random factors. Contrasts were also performed to compare each mixture and its mid-component average (Table 2.6). A subset of data was formed to compare yield of mixtures and their components in monoculture (only run for mixtures showing significantly higher yield than their midcomponent). Pearson's correlation coefficient was performed by 'PerformanceAnalytics' package to find the correlation among continuous variables (Carl and Peterson 2010).

A combined data analysis of eleven environments (the combination of location and year-excluding Certified Organic in 2016 because of no yield data) was conducted using linear mixed-effects model, in which environment was fixed and replication was random; to examine the difference in yield among environments. This combined data was also used to compare the differences between mixtures and their respective components by using the linear mixed-effects model (Pinheiro et al. 2017), in which entry was kept fixed, while environment and replication nested within environment were treated as random factors.

Yield stability analysis was conducted using Additive Main Effects and Multiplicative Interaction (AMMI) Model in 'agricolae' package (de Mendiburu 2016). The AMMI model has been used extensively for testing multi-environment yield trials for two main purposes: 1) understanding complex genotype by environment interaction to exploit both broad (stability) and narrow adaptations (adaptability) and 2) increasing accuracy to improve recommendations, repeatability, and selections (Gauch 1988; 2013). For the purpose of stability analysis, the six locations by two years were considered as eleven environments (excluding Certified Organic), and each entry was considered as a genotype. AMMI stability value (ASV) was obtained based on the first and second interaction principal component axis scores of AMMI model for each genotype. Genotypes were considered stable when the AMMI stability values were close to 0. Yield stability was also visualized through genotype plus genotype by environment (GGE) biplot graph which was supported by Yan et al. (2000). This biplot graph was constructed by the first two symmetrically scaled principal components (PC1 and PC2), in which the genotype by environment interaction effects influenced PC1, and the genotype effects influenced PC2 (Gauch 2006). A genotype was identified stable when the projection from the biplot origin was short compared to other genotypes. For the purpose of adaptability analysis, the genotype by environment interaction was detected when the sum of the first two principal components was more than 50%. The interaction was visualized in GGE biplot graph when a genotype and an environment located close to the external parts of the graph (Crossa 1990). A contour line was formed in the biplot graph to separate the genotypes which were more responsive than others.

A diallel analysis outlined by Griffing (1956) Model 1, Method 2 was performed in conventional and organic environments in Edmonton, and combined eleven environments in western Canada to estimate general combining ability (GCA) and specific combining ability (SCA) for five cultivars and their possible ten two-cultivar mixtures through AGD-R (Analysis of Genetic Designs with R for Windows) version 4.0 (Rodríguez et al. 2015). Cultivars and mixtures were considered analogous to parents and crosses respectively since both parents contribute equally to the crosses, whereas each mixture consisted of balanced contribution from two components (Gallandt et al. 2001). GCA and SCA will be referred to as general mixing ability (GMA) and specific mixing ability (SMA) respectively for the performance of cultivar mixtures (Knott and Mundt 1990). GMA was used to describe the average performance of a cultivar in mixtures and SMA was used to explain the deviation in performance of a mixture from that predicted by the GMA of both components (Knott and Mundt 1990). Springer et al. (2001) defined an SMA effect = 0 to indicate that each cultivar's contribution is equal to its expected share. An SMA effect >0 denotes the compatibility between two cultivars or a greater contribution of each cultivar than its expected share. An SMA<0 suggests an incompatibility between two cultivars or a reduced contribution of each cultivar than its expected share.

2.5 Results

2.5.1 The performance of sole cultivars and mixtures under conventional and organic environemts

Our results showed that the main effects of entry and management practice on grain yield were significant ($p<0.001$ and $p<0.05$ respectively), but the entry by management interaction was not significant ($p>0.05$) (Table 2.10). The mean yield in the organic environment (4.51 t ha^{-1}) was 19 % lower ($p<0.05$) than that under the conventional environment (5.59 t ha^{-1}). We found that the mixture G-C-L and Gl-L yielded significantly higher ($p<0.05$) than their mid-component averages in the conventional and organic environment respectively (Table 2.10; Figure 2.3). The highest-yielding entry was a three-component mixture (G-C-T) (5.92 t ha^{-1}) in the conventional environment, while CDC Titanium in the organic environment (Table 2.10; Figure 2.4). In the opposite, Lillian yielded the least in both environments (Table 2.10; Figure 2.4).

General mixing effect (GMA) on grain yield was highly significant ($p<0.001$) in both environments (Table 2.7), implying some cultivars contributed to higher yields than others in mixtures. Specific mixing effect (SMA) on grain yield was not significant ($p>0.05$), indicating that GMA of each combination accounted for the differences in yield observed among mixtures. Under the conventional environment, Carberry showed the highest significant GMA for grain yield (Table 2.8), pointing out that this cultivar was better than other cultivars as a component in mixtures. Lillian showed the lowest significant GMA, revealing the inferiority of this cultivar as a component in mixtures. The largest SMA effect was the positive interaction between Go Early and Carberry, while the smallest SMA effect was the negative interaction between Glenn and CDC Titanium even though SMA was statistically nonsignificant. Under the organic environment, CDC Titanium was superior to other cultivars (highest significant GMA), while Lillian was the opposite (lowest significant GMA). Glenn and Lillian were the most compatible (highest significant SMA), whereas Carberry and Lillian were the least suitable (lowest SMA) for mixing.

On average, the conventional environment produced significantly higher ($p<0.05$) grain protein content than the organic counterpart (14.45 % compared to 14.04% respectively) (Table

2.10), which may be likely due to low nitrogen availability in the low-input environment (Table 2.3). Entries differed considerably ($p<0.001$ and $p<0.05$) in grain protein content in conventional and organic environments, respectively (Table 2.10). We found that Lillian was the top entry (15.89 %) in the conventional environment (Table 2.10; Figure 2.5), which may be attributable to *Gpc-B1* triggering early flag leaf senescence and efficient N remobilization from leaves to grains (Uauy et al. 2006). The mixture Gl-L yielded the highest grain protein (14.74 %) in the organic environment (Table 2.10; Figure 2.5), which may be due to nitrogen use efficiency between two component cultivars under low-input condition. Comparing with the mid-component averages, the mixture C-Gl increased ($p<0.05$) protein in the organic environment, while four mixtures (C-L, Gl-L, G-Gl-L, C-Gl-L) had reduced grain protein content in the conventional environment (Table 2.10; Figure 2.5). Generally, the protein content of all cultivars and mixtures were high in both conventional and organic environments, with values above the minimum standard for CWRS of 13.5 %

A highly significant difference ($p<0.001$) among entries in gluten strength quality was found in both environments (Table 2.10). Go Early and Glenn yielded the strongest gluten quality in the conventional and organic environments respectively (Table 2.10; Figure 2.6). In the contrast, Carberry and Lillian produced the weakest gluten strength in conventional and organic environments, respectively (Table 2.10; Figure 2.6). We identified a significant ($p<0.05$) entry by management interaction for this quality, with some entries having reduced gluten strength (e.g Go Early, G-T), and the others had improved gluten strength (e.g Carberry, Gl-T, Gl-L) in the organic environment. Some mixtures strengthened gluten compared to their mid-component averages in this environment, containing G-L, Gl-L, and C-T-L.

Entries differed ($p<0.001$) on falling number only under the organic environment, and the mixture T-L showed the smallest sprouting damage in both environments (453 and 458 seconds respectively) (Table 2.10; Figure 2.7). No significant entry by management interaction on this parameter was found. The mixture G-C-L and G-T-L increased sprouting damage compared to their mid-component averages in the conventional and organic environment respectively. In the organic environment, the mixture T-T decreased significantly ($p<0.05$) sprouting damage than its mid-component average. Generally, all cultivars and mixtures in both environments met the standard requirement of falling number which should be above 300 seconds.

Weed biomass was collected only in the organic environment since herbicides were used to control weeds in the conventional environment. There was no significant ($p>0.05$) difference in the biomass of weeds among entries, although they differed in grain yield (Table 2.11). The inherent abundance of weeds in this environment may have been the result. No mixtures suppressed weeds better ($p>0.05$) than their respective components. Plant height was highly significantly different ($p<0.001$) among entries in both environments (Table 2.11), and Go Early was the tallest, while the semi-dwarf cultivar Carberry was shortest regardless of environments. Lodging rate was assessed only under the conventional environment with the average score of 4.2 on a 0-9 rating scale (Table 2.11). Meanwhile, lodging incidence was negligible under the organic environment in both years, which may be due to lower average plant height (88.58 cm compared to 99.46 cm). Cultivars (CDC Titanium, Lillian, and Go Early) were prone to lodging, while Carberry and Glenn were resistant to lodging due to their lower height and stronger stem. Mixing Carberry with Go Early and Lillian significantly reduced ($p<0.05$) lodging damage compared to the mid-component average.

Entries had a significant difference ($p<0.01$) in the number of fertile tillers under the conventional environment (Table 2.11), with CDC Titanium having the greatest number of tillers regardless of environments (1161 and 829 tillers) (Table 2.11; Figure 2.8). We found no significant difference in tiller number between two environments ($p>0.05$). Two mixtures (C-T and C-L) were surpassed significantly ($p<0.05$) by their respective components in tiller establishment in the conventional environment. Light interception was only measured in the conventional environment due to the presence of weeds in the organic counterpart, where it might be misleading. Entries intercepted radiation differently ($p<0.05$), and the mixture of Glenn and Lillian was the only entry capturing significantly more ($p<0.01$) sunlight than the average of its components (Table 2.12).

Test weight (TW) and thousand kernel weight (TKW) were highly significant ($p<0.001$) among entries in both environments (Table 2.12). We recognized that all cultivars and mixtures in both environments were above the minimum 75 kg hL^{-1} for a No.1 CWRS grading. Comparing to the mid-components, the mixture of C-Gl-L increased TW ($p<0.05$) in the conventional environment, while the mixture G-C-L decreased TW ($p<0.05$) in the organic environment. The entry by management interaction on TKW was considerable ($p<0.01$), and almost all cultivars and mixtures had comparable TKW except some mixtures had increased TKW in the organic environment (e.g Carberry, C-L, Gl-T, C-T-L) (Table 2.12; Figure 2.11). Seven mixtures had significantly higher TKW than their mid-component averages in the conventional environment, namely C-Gl, C-T, G-C-L, G-Gl-T, G-Gl-L, C-Gl-T, and C-T-L. In the organic environment, three mixtures (Gl-T, Gl-L, and G-Gl-T) showed significantly higher ($p<0.05$) TKW than the averages of their components, whereas TKW decreased ($p<0.05$) in the mixture G-C-T.

In the conventional environment, our results revealed that plant height showed a negative relationship with grain yield (Table 2.18). Tall morphology contributed to lodging as the abiotic stresses (e.g heavy rain, strong wind) occurred occasionally over the two years (Appendix 4.12). As a result of the weather, lodging damage was negatively associated with grain yield (Table 2.18). Lodging was also negatively correlated with protein content, gluten strength, and sprouting damage (Appendix 4.12). Light interception was positively correlated with grain yield, suggesting the efficiency in converting photosynthetically active radiation to dry matter, especially seed.

In the organic environment, grain yield was negatively correlated with time to heading and weed biomass but positively correlated with the number of tillers (Table 2.19). Weed biomass showed a positive correlation with plant height, heading and maturity time, but a negative association with tiller number. Grain protein content was positively associated with grain yield in the organic environment (Table 2.19), but not in the conventional environment (Table 2.18).

2.5.2 The performance of sole cultivars and mixtures in western Canada

Generally, the precipitation was higher in 2017 compared to that in 2016 (Table 2.2; Figure 2.2). The precipitation tended to increase from the South to the Northwest, while the average temperature decreased. In Edmonton, rainfall appeared to spread out evenly throughout the year, while in Beaverlodge more rainfall shifted to the end of the growing season. Heavy storms caused lodging in Edmonton and Kernen in both years, and in Beaverlodge in 2016. Early snowfall caused lodging in the Certified Organic trial in 2016 due to late harvesting. Wheat midge infected crops in all locations. Stripe rust and wheat stem sawfly were found in Lethbridge in both years.

The combined location-year analysis revealed a highly significant ($p<0.001$) difference in yield amongst eleven environments (Table 2.5). The mean yield in Edmonton Conventional in both years was highest (5.7 t ha^{-1} in 2017 and 5.48 t ha^{-1} in 2016) due to relatively high precipitation, followed by those in Kernen, (5.01 t ha^{-1} in 2017 and 4.77 t ha^{-1} in 2016 (Table 2.5; Figure 2.12). The lowest yield of 3.29 t ha^{-1} was detected in Lethbridge in 2016, which may be attributed to the limited precipitation (Table 2.2; Figure 2.2), the incidence of stripe rust, wheat midge, and wheat stem sawfly. Edmonton Organic yielded similar to Beaverlodge but lower than other conventional environments except for Lethbridge in 2016. Among entries, CDC Titanium yielded highest (5.16 t ha^{-1}), whereas the lowest-yielding entry was Lillian (4.14 t ha^{-1}) (Table 2.15). Mixtures ranked between these two cultivars. The mixtures Gl-L and G-Gl-L produced significantly higher ($p<0.001$, $p<0.05$ respectively) grain yield than the averages of their midcomponents.

Across environments in western Canada, the effect of GMA on grain yield was highly significant, while SMA had no significant effect (Table 2.7). CDC Titanium showed the highest significant GMA, followed by Carberry, indicating the excellent general mixing ability of these two cultivars in mixtures (Table 2.8). Lillian had the lowest significant GMA, showing its poor general mixing ability in mixtures. CDC Titanium and Lillian also yielded the highest and lowest respectively, indicating that GMA can be predicted by the performance of each component in pure lines. Glenn and Lillian showed the most compatibility in mixing (highest significant SMA), whereas Go Early and CDC Titanium were the least suitable for mixing (lowest SMA).

The effect of entry on yield performance was highly significant ($p<0.001$) in three locations (Edmonton Conventional, Edmonton Organic, and Kernen), and significant ($p<0.05$) in Lethbridge (Table 2.10; Table 2.14). No significant difference in yield among entries was found in Beaverlodge. The relative yield (RY) of G-C-L was positive in Edmonton Conventional and Kernen, and that of Gl-L was positive in Edmonton Organic, Beaverlodge, and Kernen (Figure 2.3; Figure 2.15; Figure 2.16). The mixture G-Gl-L had the positive RY at Beaverlodge and Kernen (Figure 2.15; Figure 2.16). Yield benefit was also found in C-L, T-L, C-T-L, and Gl-T-L in Kernen (Table 2.16; Figure 2.16). No mixtures significantly ($p>0.05$) outperformed the best component cultivars (Figure 2.13; Figure 2.14). We found yield penalty in the mixture of G-T and G-C-T in Beaverlodge and Lethbridge respectively.

Go Early was the most stable cultivar regardless of environments, followed by Gl-T-L, Carberry, G-L, and G-C (Table 2.13; Figure 2.17). In the analysis of variance for AMMI model, the main effects, genotype (entry) and environment, were highly significant ($p<0.001$), and genotype by environment interaction was significant ($p<0.01$) (Table 2.11). In AMMI model analysis, the first two principal components (PC1 and PC2) were highly significant ($p<0.001$), accounting for 27.1 and 24.6 % of the interaction variation respectively (Table 2.9; Figure 2.17).

Together, PC1 and PC2 made up 51.7 % of the genotype (entry) and genotype by environment interaction variation so the interaction was noteworthy. A biplot having PC1 and PC2 was sufficient to explain the adaptability of genotypes. For instance, the mixture G-C-L performed the best in Edmonton Conventional and Beaverlodge in 2016 (Figure 2.17). The mixture C-L was adaptive to Beaverlodge in 2016, while in 2017 this location enhanced the performance of G-Gl-L. Lillian was found to be responsive to Lethbridge in both years. The mixture G-T showed suitability to Edmonton Organic Early in both years.

In a combined analysis, Glenn matured later than other entries (Table 2.13). Entries differed significantly ($p<0.001$) in maturity in all locations, whereas in heading time in Edmonton Conventional and Edmonton Organic (Table 2.14). Mean heading time was lower in Edmonton Organic (50 days) than that in Edmonton Conventional (60 days). Similarly, entries matured earlier in Edmonton Organic (87 days) than Edmonton Conventional (98 days). Beaverlodge showed longer mean maturity (110 days) than remaining locations.

Test weight (TW) and thousand kernel weight (TKW) were greatly different ($p<0.001$) among entries in Edmonton Conventional, Edmonton Organic, and Certified Organic (Table 2.12; Table 2.15). Mean TW in Edmonton Conventional exceeded that in Edmonton Organic and Certified Organic (81.95 kg hL^{-1} > 81.23 kg hL^{-1} > 77.69 kg hL^{-1}). Mean TKW was higher in Edmonton Organic than that in Edmonton Conventional and Certified Organic (40.8 g > 39.11 g > 35.6 g). In Certified Organic, four mixtures (G-L, C-L, Gl-L, and Gl-T-L) showed significantly lower TKW than their midcomponents (Table 2.15).

Entries differed highly significant ($p<0.001$) in grain protein content in a combined analysis, and no mixtures showed higher protein than their respective components ($p<0.05$) (Table 2.13). Lillian dominated other entries in protein content (14.48%) due to *Gpc-B1* gene. Separately, no significant ($p>0.05$) difference was found in protein content amongst entries in Edmonton Organic, Lethbridge, and Kernen, while Edmonton Conventional, Certified Organic, and Beaverlodge showed highly significant ($p<0.001$) differences (Table 2.10; 2.15). Mean protein content was lowest in Certified Organic (11.7%) due to very low N availability (Table 2.3; Table 2.15), while the highest was found in Edmonton Conventional (14.54%) due to fertilizer application in both years (Table 2.10). In Kernen, the mixture T-L had significantly lower ($p<0.05$) protein content than its midcompoent.

Plant height was significantly ($p<0.001$) different between entries in all locations (Table 2.11; Table 2.16). The mean plant height was smallest at Lethbridge (81.73 cm) (Table 2.16), and highest at Edmonton Conventional (99.46 cm) (Table 2.11). Among the cultivars, Go Early was the tallest (96.33 cm) and Carberry was the shortest (82.61 cm) in a combined-environment analysis. Lodging score was recorded at four locations. Entries differed ($p<0.001$) for lodging in Edmonton Conventional, Certified Organic, Kernen, and ($p<0.01$) in Beaverlodge (Table 2.11; Table 2.16). Carberry and Glenn resisted lodging better than other cultivars in all locations. The mixture of Go Early (tall), Carberry (short), and Lillian (medium) reduced lodging ($p<0.05$) compared to its mid-component average in Edmonton Conventional (Table 2.11) and Kernen (Table 2.16). Seven mixtures including C-L, Gl-L, G-C-T, G-Gl-T, C-Gl-L, C-T-L, and Gl-T-L resisted lodging better than their mid-component averages in Kernen. The mixture of Go Early and CDC Titanium significantly ($p<0.05$) resisted lodging at Beaverlodge, while the mixtures C-T and Gl-L significantly ($p<0.05$) increased lodging compared to their mid-component averages in Certified Organic and Beaverlodge respectively.

Overall, in a combined analysis, five mixtures including G-C-Gl, G-C-T, G-C-L, G-Gl-L, and G-T-L showed significantly lower falling number than their mid-component averages (Table 2.13). Entries in Edmonton Conventional and Lethbridge did not differ ($p>0.05$) for falling number (Table 2.10; Table 2.17). However, entries differed ($p<0.001$) in Edmonton Organic and Certified Organic, and Beaverlodge ($p<0.01$) and Kernen ($p<0.05$) (Table 2.10; Table 2.17). Three mixtures (G-Gl, G-C-Gl, and G-T-L) in Certified Organic and three mixtures (G-L, G-T-L, and C-Gl-T) in Beaverlodge were found to have significantly greater ($p<0.05$) sprouting damage than the averages of their pure stands (Table 2.17). The mean falling numbers of cultivars and mixtures were higher than 300 seconds (the minimum accepted standard) at all locations except Beaverlodge which experienced high precipitation in August 2016 and severe lodging before harvesting (Table 2.17; Figure 2.2).

The mixture C-T-L strengthened gluten compared to its mid-component average in a combined analysis (Table 2.13). Entries differed ($p<0.001$) in Edmonton Conventional, Edmonton Organic, Certified Organic, Beaverlodge ($p<0.01$) and Kernen ($p<0.05$) (Table 2.10; Table 2.17). The mean gluten was strongest at Beaverlodge (32.24 mL) but weakest at Certified Organic (24.37 mL) due to limited N (Table 2.3). Only one mixture (G-L) exhibited a decrease ($p<0.05$) in gluten strength compared to its mid-component average at Lethbridge (Table 2.17); however, this mixture had enhanced ($p<0.05$) gluten strength in Edmonton Organic (Table 2.10) and Beaverlodge (Table 2.17). Results also indicated that mixing Glenn and Lillian ($p<0.05$) improved gluten strength in Edmonton Organic (Table 2.10) and Certified Organic (Table 2.17). Other mixtures that resulted in increased ($p<0.05$) gluten strength were C-T-L in Edmonton Organic, G-T and T-L in Certified Organic, and G-C, G-T-L, C-Gl-T and Gl-T-L in Beaverlodge.

Our results showed that the relationship between maturity and grain yield was strongly negative in Lethbridge and Kernen but weakly positive in Beaverlodge (Table 2.18). Plant height showed a negative relationship with grain yield in Edmonton Conventional and Lethbridge but a positive association with grain production in Kernen and Beaverlodge. Lodging significantly reduced grain yield in Edmonton Conventional and Kernen.

2.6 Discussion

2.6.1 Sole cultivars and mixtures in conventional and organic environments

In this study, the organic and conventional locations in Edmonton were less than 1km apart with similar precipitation and temperatures across years; hence the difference between the two environments are likely due to different management practices, soil fertility, and weed pressure. Our pre-seeding soil test reported that in 2016, the conventional location had greater N concentration, while in 2017, higher N concentration was found in the organic location. Nitrogen shortage in the conventional location was compensated by the fertilizer application in the second year, meaning N levels were always higher in this environment.

We found that both cultivars and their mixtures decreased productivity in the organic environment, which was coincident with other studies (Entz et al. 2001; Kitchen et al. 2003; Mason & Spaner 2006; Mason et al. 2007; Kamran et al. 2014). Weed competition plays a significant role in yield decline (Blackshaw 1994, Tuomisto et al. 2012), and a negative relationship between weed biomass and grain yield was found in our organic environment, suggesting that weeds competed with crops for growth-limiting factors such as sunlight, space, water, and nutrients (Mason et al. 2007). We also observed more diverse perennial weed species under organic than conventional environment such as Canada thistle [*Cirsium arvense* (L.) Scop.] and dandelion (*Taraxacum officinale)* which are reported to be more problematic than annual weeds due to both sexual and asexual reproduction (Samuel and Guest 1990; Schonbeck and Tillage 2011). Moreover, the organic trials were seeded later in both years to stimulate weed germination and destroy weed growth, which was founded to reduce grain yields (Ciha 1983; Subedi et al. 2007; Gao et al. 2012). Weed management carried out by delayed seeding in combination with pre-seeding tillage can affect yield negatively due to reduced moisture in the tilled soil and delayed harvest with the increased risk of frost damage (Bàrberi 2002; Mason and Spaner 2006). This is a confounding factor of the present experimental design, reflecting the common cultural practice applied by organic growers to control early season weed stress.

In our soil test, P concentration was sufficient in both environments over years, while N was lower in the organic environment in the first year. Bàrberi (2002) concluded that nutrient deficiency was also responsible for the grain yield reduction in organic systems. Typically, organic crops rely upon organic fertilizers (manure and compost) which release nutrients (especially N) at a slower pace compared with inorganic counterparts (Bàrberi 2002; van Bueren et al. 2011; Pekrun et al. 2013). Hence, organic fertilizers may not provide crops adequate available nutrients timely for growth and development (Bernal et al. 2017), which also explained the low yield performance in our organic environment. Because of these typical constraints, there is a growing demand to select cultivars or mixtures with increased performance in organic systems (Mason et al. 2007; Kaut et al. 2009). A number of studies reported several cultivars, including Walworth, AC Barrie, and Garnet, suited to the organic environment due to their exhibited cross-over interaction with this system (Nass et al. 2003; Carr et al. 2006; Mason et al. 2007). Yet, no significant interaction between entry and management was investigated in this study, implying that both environments should be considered separately when recommending cultivars and mixtures.

We selected five cultivars based on the contrasting characteristics in morphology, physiology, biotic, and abiotic resistance abilities with the intention of maximizing mixing benefits. For grain yield, the general mixing ability was a more important effect than specific mixing ability in both environments as Carberry and CDC Titanium were better mixers than other cultivars probably due to their innate yielding ability in pure stands plus the capacity to influence mixtures' performance through intraspecific competition; in the opposite way, Lillian turned out to be not desirable for mixing due to its low yielding potential.

Under the conventional environment, we found that the top-yielding entries were mixtures. Some studies reported yield benefit of mixtures derived from temporal, spatial, and physiological complementation in resource utilization (Finckh 2008; Faraji 2011; Costanzo and Bàrberi 2014; Barot et al. 2017). However, under such a desirable environment, the resource demand of each component was fulfilled individually so the mixing benefit between components may not be significant except under biotic and abiotic stresses (Borg et al. 2017). During the experimental period, we observed that biotic pressures (disease and weed problem) were not problematic, while the abiotic factors (heavy storm and rain) caused serious lodging which we found to have negative association with grain yield apparently due to the disrupted mineral translocation and carbon for filling grains (Berry and Spink 2012); the semi-dwarf cultivar Carberry had higher grain production due to improved lodging resistance compared to other cultivars. The top-yielding mixtures appeared to have Carberry as a component which provided physical support to susceptible components to continue to stand up without severe displacement of stems and roots from the vertical placement to photosynthesize and take up soil nutrients for filling grains. Moreover, high grain yield of Carberry may also be attributed to its response to high nitrogen application in semi-dwarf cultivars through high nitrogen leaf content and improved sink capacity in grains (Blackman 1978; Makino 2011), which likely compensated yield damage from lodged components in mixtures. The mixture G-C-L improved yield compared to its mid-component average, due to the inclusion of Carberry, as this mixture reduced lodging damage compared to its mid-components.

Under the organic environment, the top-yielding mixtures tended to have CDC Titanium as a component which yielded the highest; the contribution of this cultivar to the overall performance of mixtures was likely due to its weed competitive ability through high number of tillers, earliness, and wheat midge tolerance which has been speculated to account for approximately 11% of yield advantage in a study (Vera et al. 2013). Since the early-heading and high-tillering cultivar may suppress weed development and the later-heading and low-tillering cultivar can avoid the competition from weeds; however, the superior cultivar may also compete with the weaker ones as we found three mixtures having CDC Titanium had negative SMA. Additionally, yield benefit of CDC Titanium derived from wheat midge tolerance likely also played a significant role in mixtures' response by compensating yield loss due to shriveled grains of wheat-damaging components. Mixtures yielded poorly in both environments occurred to have Lillian as a component likely due to its low yielding potential; stem soliness of Lillian has been assumed to reduce yield because of the allocation of photosynthate to pith in stems rather than to grains, especially in slight wheat stem sawfly-damaging areas (McNeal et al. 1965; Weiss and Morrill 1992), or *Gpc-B1* gene in Lillian can accelerate time to maturity, reduce the grain filling period, and lead to low yield potential through reduced grain weight (Brevis et al. 2010).

We investigated that the specific mixing ability effect was small and not statistically significant in both environments, indicating that mixtures' response can be obtained by the general mixing ability effect. However, a few notable mixtures were observed, such as G-C and Gl-L which were the most compatible combinations in the conventional and organic environments respectively; the former mixture had two components expressing contrasting characteristics in maturity, height, and lodging resistance, while the later mixture had two components differing in heading, maturity, and lodging resistance. These results agree with other findings when components varying in agronomic traits, disease resistance, freezing tolerance, and lodging protection showed mixing benefit (Sammons and Baenziger 1985; Mille et al. 2006; Cowger and Weiz 2008; Mengistu et al. 2010; Zhou et al. 2014; Vrtilek et al. 2016). In our study, variation in heading and maturity possibly allowed components to avoid the competition for resources simultaneously, especially in low-input environment; diversity in height may improve light interception and reduce disease because of the increase aeration and less humidity within the crop canopy; lodging damage from susceptible cultivars can be reduced by leaning on the resistant component in mixtures (Borg et al. 2017). In another way, Gl-T and C-L were not favourable mixtures in the conventional and organic conditions respectively; two components in the first mixture shared a similar height and heading time which may increase competition for sunlight and soil resources concurrently; two components in the second mixture had complementary characteristics in phenological traits and lodging resistance which were supposed to increase the mixing effect, suggesting another unknown mechanism (e.g similar root system or water use pattern) was responsible for the increased competition when combined.

Although increased grain production has often been achieved in conventional environments (Nelson et al. 2011), organic environments may offset a yield disadvantage through high grain quality which sometimes brings the high economic return to organic farmers (Mason and Spaner 2006). Interestingly, we found a significant entry by management interaction on gluten strength as some entries (Carberry, Gl-T, Gl-L) performed better under organic environment. This benefit would give organic producers increased economic value as excellent baking quality is worth more under the Canadian grading system (Kaut et al. 2009). Cultivar mixing strategies are also suggested to improve the baking quality (Lee et al. 2005; Zhou et al. 2014) when weak-gluten cultivars are combined with strong-gluten cultivars. This advantage may be due to either better nitrogen use efficiency between components in low-input environments or the compensation effect from stronger-gluten cultivars (Costanzo and Bàrberi 2014). The TW of most mixtures was equal to the mean TW of components in both environments, and all mixtures met the TW requirement for CRWS grade 1 (at least 75 kg hL^{-1}), offering the premium price for mixed spring wheat grains. Falling number of cultivars and mixtures grown in both environments were all above 300, indicating the preferred level of enzyme activity for baking (Suas 2008), or otherwise the dough will become soft and sticky due to sprouted grains (Migliorini et al. 2016).

Grain protein content and grain yield primarily determine the economic value of wheat (Dai et al. 2012), and there is a desire to achieve these traits concurrently (DePauw et al. 2007). However, a number of works have found their negative relationship ranging from -0.2 to -0.8 (Halloran 1981; Loffler and Busch 1982; Guthrie et al. 1984; O'Brien and Ronalds 1984; Costa and Kronstad 1994) due to genetic incompatibility (linkage, pleiotropy), partitioning efficiency, and competition between C and N for photosynthetic energy and carbon skeleton (Bogard et al. 2008). Changing that correlation has posed a real challenge for wheat breeders, and wheat cultivar mixtures have been proposed to break the negative relationship through the complementary traits of each cultivar (Dai et al. 2012; Zhou et al. 2014). As expected, we observed a positive correlation between grain yield and protein content in the organic environment, indicating some mixtures resulted in a potentially high-yielding combination with enhanced protein content. For instance, the mixture of Lillian (high protein) and Glenn (higher yield) yielded as much as Glenn, with similar protein content to Lillian. Similarly, the mixture of Carberry (high yield) and Glenn (higher protein) produced as high yield as Carberry with comparable protein content as Glenn. A similar result was found by Sarandon and Sarandon (1995) when they mixed a modern (high yield) with an old wheat cultivar (low yield but high protein) in an environment which received no nitrogen. These results are expected to assist organic producers to achieve high grain yield and protein content simultaneously through mixing practice.

Weed infestation is the major biotic obstacle as the competition for nutritional resources between weeds and crops can be intense (Degenhardt et al. 2005; Mason et al. 2007). Hence, in addition to yielding well, organic crops are required to be highly competitive (Bàrberi 2002). Competitive cultivars displayed tall height, early season vigor, earliness, elevated PAR interception, high number of fertile tillers, high early biomass accumulation, and high amount of allelochemicals (Mason and Spaner 2006). We identified that plants producing more tillers and flowering and maturing early reduced weed biomass, suggesting these traits are good predictors of weed suppression ability. These results agree with those of Hucl (1998), Korres and Froud-Williams (2002), and Mason et al. (2008) who reported that tillering capacity influenced yielding ability, while early heading and maturity provided plants the time window to escape increasingly heavy competition for soil nutrients and moisture. Only early heading and tiller establishment contributed to yield performance in the present study, and the best-yielding entry was CDC Titanium which produced the highest number of tillers and headed early. In contrast, Lillian began heading later than all other entries and produced fewer tillers, resulting in the lowest yield. In the present study, tall stature did not result in low weed biomass; a result contradicting other studies (Mason et al. 2007; 2008), suggesting height alone may not be a good trait of competitive ability in the organic environment. The semi-dwarf cultivar Carberry had lower weed biomass than taller cultivars such as Go Early, Glenn, and Lillian, which may be due to other contributing factors including leaf orientation (Huel and Hucl 1996; Hoad et al. 2005) or below-ground traits such as early root formation (Kruepl 2006) or allelochemicals released from plant roots to suppress weeds (Zuo et al. 2005). Mixtures are also considered to control weed development due to the complementary agronomic traits which can utilize nutrients more efficiently than cultivars in monoculture and leave fewer resources for weeds (Liebman and Staver 2001). Lazzaro et al. (2017) reported that mixtures of twelve wheat cultivars significantly reduced weed biomass although mixing so many cultivars may be practically difficult. In another study, a mixture of semi-dwarf and medium-tall wheat cultivars tolerated competition from weeds despite high weed biomass (Kaut et al. 2009). Height variation between components can generate a unique canopy structure capturing more sunlight for plant photosynthesis and less for weeds to germinate and develop (Sage 1971). In this study, no particular mixtures suppressed weeds better than their respective components although component cultivars were selected for different height, suggesting that height diversity was not adequate to buffer against the heavy competition from weeds. Moreover, we also found that the mixture Gl-L improved both yield and gluten strength comparing to it components had the highest weed biomass. Thus, it may be risky to adopt this mixture when weeds may become problematic in the future.

2.6.2 Sole cultivars and mixtures in western Canada

Our tested locations were representative of the typical climate in western Canada. Over the experimental period, the weather patterns varied across locations with different biotic and abiotic stress events. Because of that variation, it may not be always possible to predict which cultivar will yield the best in the next growing season; hence, the safest option is to grow mixtures in order to reduce risk (Zhou et al. 2014). Since this agronomic practice has been well-known for stabilizing yield under the variable growing conditions due to complementation, compensation, and facilitation effects between components (Wolfe and Gacek 2001; Kaut et al. 2009; Cowger and Weisz 2008; Zhou et al. 2014; Migliorini et al. 2016). In the present study, we found that Go Early was the most stable, which may be due to its widespread testing before releasing. The mixture Gl-T-L was the second most stable, and three components each began heading (CDC Titanium<Glenn<Lillian) and reached maturity (CDC Titanium<Lillian<Glenn) separately, which may have reduced competition for soil nutrients and humidity at the same time. Several authors characterized this effect as the complementation interaction, in which components exploit the resources differently temporally, leading to satisfied demand for each component cultivar without compromising the overall performance (Finckh 2008; Faraji 2011; Costanzo and Bàrberi 2014; Barot et al. 2017). The facilitation effect from Glenn (physical support against lodging) was also likely to contribute to the mixture's stability in the unpredictable climate of western Canada. The compensation effect from CDC Titanium (wheat midge resistance) can be another contributing factor as its high yield potential can offset the lower yield from Glenn and Lillian which were susceptible to wheat midge infestation. Hence, western farmers may prefer this mixture to Go Early in reducing the risk of yield variability and achieving an acceptable production. However, the lack of uniform maturity among cultivars may make harvesting a challenge (Bowden et al. 2001; Finckh 2008; Fariji 2011; Borg et al. 2017). It was observed that this mixture matured close to Lillian (medium maturity), which may not be a real technical concern. Moreover, the harvesting time was often made by the availability of favorable drying weather rather than physiologic maturity.

Selecting cultivars or mixtures for a particular environment should also be taken into consideration to maximize the positive interaction with the local climate. Our result investigated some promising candiates for this purpose such as the lodging-tolerant mixture G-C-L for north central Alberta (Black Chernozemics soil, relatively high precipitation, and storm events during the summer) and northwest Alberta (Dark Gray Luvisols soil, high precipitation, and storm events in the end of the summer), the mixture C-L and lodging-tolerant mixture G-Gl-L for northwest Alberta, the solid-stem and stripe rust-resistant cultivar Lillan for the south Alberta (Dark Brown Chernozemics soil, low precipitation, heat stress, stripe rust, and wheat stem sawfly incidence), and the early-heading and maturity mixture G-T for the organic environment in north central Alberta (Balck Chernozemics soil, relatively high precipitation, weed infestation, and wheat midge incidence).

Another aspect of this study was to select favorable cultivars for mixing and compatible combinations across environments in western Canada. The result showed that there was a clear trend in the importance of GMA rather than SMA as the mean squares of the former were always significant, meaning the performance in pure stands was a good indicator of mixtures. The result also showed that CDC Titanium and Carberry were favorable, while Lillian was not desirable as a component in mixtures; the significant mixing benefit of CDC Titanium was likely due to its high yielding ability in the face of wheat midge infestation in western region plus its earliness to avoid heat stress and drought in south Alberta, central Saskatchewan and weed competition in north central Alberta, which in turn reduced its yield loss caused by biotic and abiotic stresses and compensated yield reduction from other damaged components in mixtures. The semid-warf Carberry also had positive GMA as this cultivar resisted to lodging very well in the situation of heavy storms and ranked high in yield in environments receiving fertilizers, which in sequence supported other tall and susceptible components physically in order to prevent them from lodging and contributed to the overall performance through its high yield. In another way, Lillian was not a good component in most mixtures as it appeared to lodge severely and yielded lowest in most environments possibly due to the broken nutrient translocation and the negative association between grain production and stem solidness in areas with minimal wheat stem sawfly damage (Weiss and Morrill 1992; McNeal et al. 1965). From those results, generally, high-yielding cultivars should be mixed to ensure acceptable production, which is in agreement with Galland et al. (2001) and Bowden et al. (2001).

Interestingly, we found that Lillian with Glenn made the most compatible pair, as their mixture improved yield compared to their mid-component across environments. The possible reason may be the variation in heading and maturity time (temporal complementation effect) to minimize the competition (Ghosh et al. 2009; Wang et al. 2016), and the physical support from Glenn (facilitation effect) to keep Lillian stand upright. In addition, there is a suggestion to remove incompatible two-way mixtures before constructing more complex mixtures (Knott and Mundt 1990; Mille et al. 2006). Although SMA was not statistically significant, we found that the mixture between Go Early and CDC Titanium was not suitable for mixing because they are agronomically identical in height, heading, and maturity, which possibly increased their competition and decreased mixing effect. Hence, mixtures should avoid the components sharing similar characteristics in those traits.

Another benefit of wheat cultivar mixtures is yield improvement compared to of their midcomponents (Kiær et al. 2009; Mengistu 2010; Borg et al. 2017). Several studies conducted in Canada concluded no yield increase under both conventional and organic environments (Pridham et al. 2007; Kaut et al. 2009). In the present case, some mixtures increased yield in four out of five test locations (including both conventional and organic environments). For instance, in north central Alberta, yield improvement was 0.52 t ha^{-1} in G-C-L under the conventional environment, and 0.4 t ha^{-1} in Gl-L under the organic environment. In central Saskatchewan, yield benefits were found in seven mixtures including C-L (0.17 t ha^{-1}), Gl-L (0.36 t ha^{-1}), T-L (0.19 t ha^{-1}), G-C-L (0.16 t ha^{-1}), G-Gl-L (0.19 t ha^{-1}), C-T-L (0.18 t ha^{-1}), and Gl-T-L (0.19 t ha^{-1}). The greatest yield increases were Gl-L and G-Gl-L (0.69 t ha^{-1}, and 0.71 t ha^{-1} respectively) in northwest Alberta. In a combined analysis, Gl-L and G-Gl-L showed 0.33 t ha^{-1} and 0.22 t ha^{-1} yield increase. Based on those results, it is possible to say that wheat cultivar mixtures had significant yield improvement compared with the mid-component averages in most cases. These mixtures will be more attractive to growers if they perform well in relative to others (Cowger and Weiz 2008). For example, G-C-L and G-Gl-L ranked one of the top entries in north central and northwest Alberta respectively. Testing these mixtures on a larger scale before recommendation should be taken into consideration.

The effectiveness of wheat cultivar mixtures on yield improvement would be evident in the presence of biotic or abiotic pressures (Borg et al. 2017). In this study, mixing short-statured and strong-straw cultivars (Carberry and Glenn) with tall-statured and weak-straw cultivars (Go Early, CDC Titanium, and Lillian) created a mutualistic benefit when lodging occurred. Our results are in an agreement with Zhou et al. (2014) who also reported a decrease in lodging incidence in a mixture of tall, medium and short wheat cultivars. However, Kaut et al. (2009) did not find any mixing effect of mixtures on lodging regardless of management practices. In non-irrigated or drought conditions, the complementary traits could facilitate water use efficiency in wheat cultivar mixtures (Fang et al. 2014; Adu-Gyamfi et al. 2015), which may lead to a yield increase (Wang et al. 2016). Yet, there were no mixtures having a higher yield than their mid-component averages in the low precipitation region of southern Alberta across the two years we conducted field trials. Height diversity between components could create a wavy canopy arrangement which may prevent sunlight from reaching the soil and reduce water loss through evaporation (Faraji 2011; Adu-Gyamfi et al. 2015); however, that benefit may not be adequate to buffer against severe water shortage.

Normally millers blend different cultivars' flour to attain quality consistency, but this blending could also be executed by mixing wheat cultivars ahead of planting. Quality is one of the most important factors, and wheat mixtures have to be selected to meet the market requirement for a certain use. That implies that mixtures would be preferred if they at least had comparable end-use quality as the component cultivars (Jackson and Wennig 1997). Hence, to somewhat maintain quality characteristics, cultivar candidates for wheat mixtures should originate from the same class (Jackson and Wennig 1997). All five component cultivars in this study are from the same end-use class, which is known internationally for its high quality, and mixing them was therefore appropriate. From the results, we found that the protein content of most mixtures was within the range of the lowest and highest cultivar in pure stands, which agrees with the findings of previous studies (Jackson and Wennig 1997; Kaut et al. 2009). Some mixtures showed the unfavorable mixture efficiencies in protein content in the location which received N-based fertilizers, which was probably due to the competition between components. A mixture consisting of a low-protein cultivar (Carberry) with another high-protein cultivar (Glenn) was significantly favorable compared to the average of their pure stands under N-limiting environment, which could be attributed to the better nitrogen use efficiency, improved exploitation of the soil and aerial space, or compensation between components (Costanzo and Bàrberi 2014).

Gluten is another unique quality aspect of wheat flour, giving it the advantage of making a wide range of products (McFall and Fowler 2009). Five CWRS cultivars selected in this study expressed strong gluten except for Lillian, although it expressed the highest protein content. Mixing this cultivar with other cultivars could mask its disadvantage. As expected, gluten was strengthened in a number of mixtures including Lillian as a component, suggesting an alternative way to compensate for the weakness in quality and additionally take advantage of high protein content, wheat stem sawfly and stripe rust resistance from Lillian; however, the poor performance of Lillian in most mixtures may prevent producers from adopting this cultivar in their mixing strategy. Additionally, we found that sprouting damage in mixtures was above the minimum requirement except for those in a high-rainfall environment with serious lodging as wheat heads fell down to the ground with high humidity and grains imbibed rainwater for germination (Kettlewell 1996). Further research should consider new mixtures with improved resistance against sprouting damage by mixing with lodging-resistant cultivars.

Across locations, the relationship between grain yield and maturity was both positive and negative. In normal growing conditions (e.g sufficient precipitation), the late maturity facilitates longer grain filling periods due to the increased post-anthesis assimilate production, which results in higher productivity (Bidinger et al. 1977; Sanchez et al. 2002). However, early maturity is a desirable trait to avoid yield loss and quality degradation because frost-free days in western Canada are limited to 95-125 days in total (Kamran et al. 2013). In locations where the annual precipitation was low (southern Alberta and central Saskatchewan), the highest-yielding cultivar, CDC Titanium, matured earlier than other entries, and it has been reported that cultivars having high production tended to mature earlier to avoid stress condition in moisture-deficit environments (Al-Karaki 2012). Taller cultivars increased susceptibility towards lodging, and this constraint increased yield loss and reduced end-use quality characteristics, which has been reported in other studies as well (Stapper and Fisher 1990; Baker et al. 1998; Berry et al. 2007).

2.7 Conclusions

The present study evaluated the potential performance of spring wheat cultivar mixtures under conventionally and organically managed systems across western Canada, in several different environments. These two systems differed greatly in weed competition and nutrient availability, which in turn decreased the overall grain yield and protein content. Excellent gluten quality of organic mixtures was possible to achieve even though grain production was lower than conventional counterparts. In the organic environment, mixtures did not suppress weeds better than component cultivars. However, we identified two agronomic traits (early heading and good tillering) that are desirable for improving competitive ability and maintaining yield under weedy conditions. Semi-dwarf and strong stem cultivars (Carberry and Glenn) resisted lodging due to abiotic pressure, and also provided susceptible cultivars in mixtures with the physical support. This gives farmers another management strategy for coping with lodging damage through growing mixtures. Across environments in western Canada, Go Early demonstrated the most stable yield, while CDC Titanium displayed the highest production. On the conditions that both stability and high yield were prioritized, a three-way mixture of Glenn (strong stem, early heading, late maturity), CDC Titanium (wheat midge tolerance, early heading, early maturity) and Lillian (late heading, medium maturity) would be the most suitable choice for western farmers facing the challenges of biotic and abiotic stresses. Our results also indicate that wheat cultivar mixtures did provide benefits to yield, grain quality characteristics, and abiotic resistance in diverse growing conditions across western Canada. Those mixing effects tended to appear by mixing CWRS cultivars expressing contrasting characteristics in plant height, heading, maturity, quality, lodging, and insect resistance. CDC Titanium and Carberry turned out to be the most favorable components in mixtures, while the mixture of Glenn and Lillian was found to be the most compatible combination for grain yield. Thus, these findings provide conventional and organic farmers a novel agronomic practice to boost yield and improve quality through biodiversity as well as potential cultivars to maximize mixing benefit.

2.8 Tables and Figures

Table 2.1 CWRS cultivars and their mixtures evaluated in conventional and organic field trials from 2016 to 2017

Entry (year of release)	Seed ratio	Abbreviation	Yield (t/ha)	Protein (%)	Maturity (days)	Height (cm)	Lodging resistance	Disease resistance		
								Common bunt	Stripe rust	Leaf spot
Go Early (2014)	Sole-crop	-	4.20	14.3	VE[a]	93	G[b]	MR[c]	I	S
Carberry (2009)	Sole-crop	-	4.32	14.0	L	79	VG	R	MR	MS
Glenn (2006)	Sole-crop	-	4.20	13.8	L	85	VG	I	MR	I
CDC Titanium (2014)	Sole-crop	-	4.36	14.5	E	87	G	I	R	MS
Lillian (2003)	Sole-crop	-	4.62	14.0	M	86	F	MR	R	MR
Go Early-Carberry	1:1	G-C								
Go Early-Glenn	1:1	G-Gl								
Go Early-CDC Titanium	1:1	G-T								
Go Early-Lillian	1:1	G-L								
Carberry-Glenn	1:1	G-Gl								
Carberry-CDC Titanium	1:1	C-T								
Carberry-Lillian	1:1	C-L								
Glenn-CDC Titanium	1:1	Gl-T								
Glenn-Lillian	1:1	Gl-L								
CDC Titanium-Lillian	1:1	T-L								
Go Early-Carberry-Glenn	1:1:1	G-C-Gl								
Go Early-Carberry- CDC Titanium	1:1:1	G-C-T								
Go Early-Carberry-Lillian	1:1:1	G-C-L								
Go Early-Glenn-CDC Titanium	1:1:1	G-Gl-T								
Go Early-Glenn-Lillian	1:1:1	G-Gl-L								
Go Early-CDC Titanium-Lillian	1:1:1	G-T-L								
Carberry-Glenn-CDC Titanium	1:1:1	C-Gl-T								
Carberry-Glenn-Lillian	1:1:1	C-Gl-L								
Carberry-CDC Titanium-Lillian	1:1:1	C-T-L								
Glenn-CDC Titanium-Lillian	1:1:1	Gl-T-L								

Source: Alberta Seed Guide, Alberta Regional Variety Advisory Committee and Alberta Agriculture and Forestry.
[a] VE: Very Early, E: Early, M: Medium, L: Late.
[b] F: Fair, G: Good, VG: Very good.
[c] R: Resistant, MR: Moderately Resistant, I: Intermediate, MS: Moderately Susceptible, S: Susceptible

Table 2.2 Weather data[a], planting and harvesting dates of tested locations from 2016 to 2017.

Year	Location	Planting Date	Harvesting Date	Precipitation (mm)						Average Daily Temperature (^{0}C)					
				May	June	July	August	September	Total	May	June	July	August	September	Monthly Average
2016	Edmonton Conventional	May 9	September 7	93.80	72.60	118.0	90.2	25.40	374.6	12.3	16.8	18.6	16.8	11.3	15.2
	Edmonton Organic Early	May 12	September 26	93.80	72.60	118.0	90.2	25.40	374.6	12.3	16.8	18.6	16.8	11.3	15.2
	Certified Organic	June 6	November 9	125.8	124.8	106.5	103.8	37.30	498.2	11.5	15.9	18.3	16.8	11.1	14.7
	Kernen	May 3	August 31	42.60	46.80	76.90	70.20	24.10	260.6	14.7	18.5	19.3	16.9	11.8	16.2
	Lethbridge	May 5	September 6	11.10	18.90	78.40	45.70	21.70	157.8	11.1	16.9	17.8	17.0	12.6	15.1
	Beaverlodge	May 11	September 24	71.50	122.3	62.20	127.0	30.80	413.8	10.0	14.2	15.3	14.8	9.20	12.7
2017	Edmonton Conventional	May 11	September 6	51.60	50.60	79.40	42.20	53.60	277.4	14.0	16.6	19.2	17.9	13.2	16.2
	Edmonton Organic Early	May 20	September 8	51.60	50.60	79.40	42.20	53.60	277.4	14.0	16.6	19.2	17.9	13.2	16.2
	Edmonton Organic Late	June 5	September 29	51.60	50.60	79.40	42.20	53.60	277.4	14.0	16.6	19.2	17.9	13.2	16.2
	Kernen	May 21	September 9	46.30	30.90	25.50	25.20	29.10	157.0	12.1	16.1	19.6	17.8	12.8	15.7
	Lethbridge	May 4	August 22	19.50	64.00	4.80	7.80	1.80	97.90	13.4	16.0	19.9	18.3	12.9	16.1
	Beaverlodge	May 23	October 3	85.30	61.30	3160	37.30	88.90	304.4	11.3	13.6	15.7	15.6	10.9	13.4

[a] Government of Canada

Table 2.3 Soil fertility levels and physical properties of Edmonton Conventional, Edmonton Organic, and Certified Organic from 2016 to 2017

Year	Site	Nutrient levels (ppm)				Soil quality		
		N[a]	P	K	S[b]	pH	EC[c](dS/m)	OM[d] (%)
2016	Edmonton Conventional	55	>60	489	16	6.1	0.85	14.2
	Edmonton Organic	24	>60	426	11	6.7	0.60	11.8
	Certified Organic	19	11	98	10	7.5	0.65	7.8
2017	Edmonton Conventional	25	58	426	12	6.3	0.50	14.7
	Edmonton Organic	59	>60	310	14	6.6	0.75	12.9

[a] Nitrate-N only, [b] Sulphate-S only, [c] Electrical conductivity, [d] Organic matter

Table 2.4. Soil classification of tested locations in western Canada

Location	Soil group[a]
Edmonton Conventional (Edmonton Research Station)	Black Chernozemics
Edmonton Organic 1 (Edmonton Research Station)	Black Chernozemics
Edmonton Organic 2 (Edmonton Research Station)	Black Chernozemics
Certified Organic (Lamont)	Black Chernozemics
Beaverlodge (Beaverlodge Research Farm)	Dark Grey Luvisol
Lethbridge (Lethbridge Research Centre)	Dark Brown Chernozemics
Kernen (Kernen Research Farm)	Dark Brown Chernozemics[b]

[a] Agricultural Land Resource Atlas of Alberta - Soil Groups of Alberta
[b] Saskatchewan Ministry of Agriculture. 2009. Soil Zones in Southern Saskatchewan.

Table 2.5. Mean grain yield of the eleven environments tested in western Canada from 2016 to 2017

Location	Year	Total precipitation (mm)	Mean site-year [a] (t/ha)
Edmonton Conventional	2016	374.6	5.48b
	2017	277.4	5.70a
Edmonton Organic Early	2016	374.6	4.30f
	2017	277.4	4.75d
Edmonton Organic Late	2017	277.4	4.49e
Beaverlodge	2016	413.8	4.75d
	2017	304.4	4.65de
Lethbridge	2016	157.8	3.29g
	2017	97.90	4.95c
Kernen	2016	260.6	4.77d
	2017	157.0	5.01c
F value			104.3
P value[b]			***
SE [c]			0.09
LSD[d]			0.16

[a] Letters indicate significant differences at $p \leq 0.001$.
[b] ***: significant at $p \leq 0.001$
[c] Standard error of the difference between two means.
[d] Least Significant difference

Table 2.6 Type of comparison and the set of orthogonal linear contrast

Contrast	Entry	Coefficients
A two-cultivar mixture	A-B	2
vs		
Respective components	A	-1
(mid-component average)	B	-1
A three-cultivar mixture	A-B-C	3
vs		
Respective components	A	-1
(mid-component average)	B	-1
	C	-1

Table 2.7 Analysis of variance for general mixing ability (GMA) and specific mixing ability (SMA) on grain yield in conventional, organic environments, and combined 11 environments in western Canada from 2016 to 2017

Source of variation	Degree of freedom	Mean squares		
		Conventional	Organic	Combined environments
GMA	4	**1.56***	**3.34*****	**5.7*****
SMA	10	0.09	0.22	0.27
Residuals				
Conventional	70	0.15		
Organic	112		0.21	
Combined environments	448			0.22

*, *** significant at 0.05 and 0.001 respectively

Table 2.8 General mixing ability (GMA) and specific mixing ability (SMA) of grain yield for five cultivars and ten two-way mixtures grown in conventional, organic environments, and combined environments from 2016 to 2017

Entry	Conventional	Organic	Combined environments
		t/ha	
Cultivars (GMA)			
Go Early	0.029	0.077	-0.013
Carberry	**0.130***	-0.0007	**0.049***
Glenn	0.097	0.076	-0.008
CDC Titanium	0.082	**0.230*****	**0.205*****
Lillian	**-0.338*****	**-0.381*****	**-0.233*****
Mixtures (SMA)			
G-C	0.161	0.081	0.059
G-Gl	-0.024	0.013	-0.007
G-T	0.074	0.085	-0.056
G-L	-0.033	0.090	0.013
C-Gl	0.058	0.070	0.014
C-T	-0.003	-0.068	-0.028
C-L	0.059	-0.267	-0.020
Gl-T	-0.115	-0.100	-0.007
Gl-L	0.110	**0.295***	**0.213****
T-L	0.160	-0.020	0.032

*, **, *** significant at p≤0.05, 0.01, 0.001 respectively

Table 2.9 AMMI analysis of variance for grain yield of five cultivars and twenty two-way and three-way mixtures under eleven environments in western Canada from 2016 to 2017

Source of variation	Degree of freedom	Sum of squares	Mean squares
Environment	10	298.41	**29.84*****
Block within Environment	22	50.03	**2.27*****
Genotype	24	29.44	**1.23*****
Genotype by Environment Interaction	240	59.77	**0.25****
PC1	33	16.19	**0.49*****
PC2	31	14.71	**0.47*****
PC3	29	9.29	**0.32****
PC4	27	7.29	**0.27***
PC5	25	5.43	0.22
PC6	23	4.07	0.18
PC7	21	1.45	0.07
PC8	19	0.76	0.04
PC9	17	0.38	0.02
PC10	15	0.19	0.01
Residuals	528	94.44	0.18
Total	824	591.85	

*, **, *** significant at p≤0.05, 0.01, 0.001 respectively

Table 2.10 Least square means of yield, grain protein, SDS sedimentation, and falling number of five cultivars and twenty two-way and three-way mixtures under conventional and organic environments from 2016 and 2017

Entry	Yield (t/ha)				Grain protein (%)		SDS sedimentation (mL)		Falling number (seconds)	
	Conventional	Rank	Organic	Rank	Conventional	Organic	Conventional	Organic	Conventional	Organic
Go Early	5.51[a]	18	4.50	14	14.69	13.76	**29.05**	**26.84**	402	374
Carberry	5.66	12	4.57	12	13.63	13.52	24.10	25.50	378	384
Glenn	5.72	10	4.49	15	14.77	14.07	**28.26**	**28.10**	356	352
CDC Titanium	5.65	13	4.99	1	14.41	13.80	25.15	25.17	383	453
Lillian	4.72	25	3.66	25	15.89	14.52	**24.82**	**24.33**	425	472
G-C	5.86	3	4.64	10	14.25	13.74	**27.33**	**26.41**	365	378
G-Gl	5.64	14	4.65	8	14.69	13.86	27.86	26.88	365	384
G-T	5.73	9	4.87	3	14.44	13.70	**27.86**	**25.23**	383	400
G-L	5.20	23	4.22	23	15.00	13.72	27.00	**27.55****	391	391
C-Gl	5.83	4	4.63	11	14.13	**14.20***	26.33	27.44	349	371
C-T	5.75	8	4.64	9	14.14	13.85	24.49	25.52	382	399
C-L	5.39	22	3.96	24	**14.32**‡‡	14.05	25.28	25.41	416	400
Gl-T	5.61	16	4.69	6	14.55	14.41	25.94	27.44	400	424
Gl-L	5.41	21	**4.47***	17	**14.55**‡‡‡	14.74	25.68	**28.08****	381	391
T-L	5.45	20	4.30	22	14.95	14.16	24.62	25.26	**453***	458
G-C-Gl	5.81	7	4.47	16	14.24	13.98	27.73	27.00	363	348
G-C-T	5.92	1	4.76	5	14.28	13.92	25.68	26.38	380	374
G-C-L	**5.82***	6	4.32	21	14.76	14.05	25.41	26.67	**336**‡‡	378
G-Gl-T	5.82	5	4.90	2	14.44	14.27	26.20	27.26	370	408
G-Gl-L	5.13	24	4.37	19	**14.59**‡‡‡	14.18	**28.25**	**27.31**	401	393
G-T-L	5.52	17	4.66	7	14.88	13.92	26.47	25.54	371	**399**‡
C-Gl-T	5.88	2	4.77	4	14.37	14.28	25.54	26.71	413	415
C-Gl-L	5.48	19	4.36	23	**14.39**‡	13.81	**26.40**	**25.63**	395	399
C-T-L	5.69	11	4.51	13	14.45	14.13	24.95	**26.67***	413	428
Gl-T-L	5.62	15	4.42	18	14.78	14.13	**26.80**	**26.18**	405	419
Mean	5.59		4.51		14.54	14.04	26.29	26.42	387	400
F values[b]										
Entry	***		***		***	*	***	***	**ns**	***
Management	*		*		*	*	**ns**	**ns**	**ns**	**ns**
Entry* Management	**ns**		**ns**		**ns**	**ns**	*	*	**ns**	**ns**
SE (Entry)[c]	0.25		0.14		0.18	0.22	0.83	0.57	25.59	14.31
SE (Management)[d]	0.06		0.06		0.08	0.08	0.74	0/74	24.77	24.77
SE (Entry x Management)	0.36		0.36		0.52	0.52	1.4	1.4	33.9	33.9
LSD[e]	0.51		0.43		0.36	0.62	1.78	1.66	51	41

[a] *, ** Mixtures had significant greater than their mid-component averages at p≤0.05, 0.01 respectively. ‡, ‡‡, ‡‡‡ Mixtures had significant less than their mid-component averages at p≤0.05

[b] ns: not significant, *: significant at p≤0.05, **: significant at p≤0.01, ***: significant at p≤0.001

[c] Standard error of the difference between two least-square means.

[d] Standard error of the difference between conventional and organic management main effects.

[e] Least Significant Difference

Table 2.11 Least square means of height, lodging rate, the number of tillers, and weed biomass of ive cultivars and twenty two-way and three-way mixtures under conventional and organic environments from 2016 and 2017

Entry	Height (cm)		Lodging rate (1-9)	The number of tillers (m^{-2})		Weed biomass (g/m^2)
	Conventional	Organic	Conventional	Conventional	Organic	Organic
Go Early	104.9[a]	92.78	4.7	976[a]	749	276.7
Carberry	88.04	81.89	2.3	1137	717	226.0
Glenn	98.70	89.48	3.2	905	770	242.7
CDC Titanium	101.3	87.11	6.0	1161	829	202.9
Lillian	100.3	89.39	5.5	976	668	374.8
G-C	98.45	88.39	3.5	924	755	207.5
G-Gl	104.5	90.23	3.5	843	736	350.8
G-T	101.3	89.30	4. 7	981	736	148.7
G-L	102.5	91.33	5.8	872	726	353.9
C-Gl	94.08	86.66	2.2	969	755	168.9
C-T	98.38	84.90	4.8	**996 ‡**	721	188.5
C-L	95.42	84.31	4.8	**911 ‡**	658	439.1
Gl-T	98.83	87.87	5.0	1116	818	198.1
Gl-L	100.7	88.49	4.5	1003	737	443.1
T-L	99.58	87.82	6.2	1008	755	283.7
G-C-Gl	99.50	89.47	3.0	928	715	376.4
G-C-T	101.07	89.92	3.5	1059	734	244.0
G-C-L	99.88	89.53	**2.67‡**	933	674	382.9
G-Gl-T	100.8	91.31	4.0	980	797	170.8
G-Gl-L	101.1	91.31	3.7	1075	767	157.2
G-T-L	103.4	91.37	5.8	1029	708	269.1
C-Gl-T	98.32	88.86	4.0	981	782	222.0
C-Gl-L	98.02	87.62	3.3	931	683	302.5
C-T-L	98.85	87.24	4.0	1012	781	348.0
Gl-T-L	98.75	88.87	4.8	931	677	307.6
Mean	99.46	88.58	4.2	985	738	275.4
F values[b]						
Entry	***	***	***	**	ns	**ns**
Management	**ns**	**ns**	**-**	**ns**	**ns**	**-**
Entry * Management	**ns**	**ns**	**-**	**ns**	**ns**	**-**
SE (Entry)[c]	1.62	1.15	0.9	78.76	60.39	99.85
SE (Management)[d]	2.15	2.15	-	36.11	36.11	-
SE (Entry x Management)	2.31	2.31	-	101.68	101.68	-
LSD[e]	3.6	2.35	1.78	168	119.85	204.72

[a] ‡ Mixtures had significant less than their mid-component averages at p≤0.05

[b] ns: not significant, *: significant at p≤0.05, **: significant at p≤0.01, ***: significant at p≤0.001

[c] Standard error of the difference between two least-square means.

[d] Standard error of the difference between conventional and organic management main effects.

[e] Least Significant Difference

Table 2.12 Least square means of test weight (TW), thousand kernel weight (TKW), and light interception of five cultivars and twenty two-way and three-way mixtures under conventional and organic environments 2016 and 2017

Entry	TW (kg/hL)		TKW (g)		Light interception (%)
	Conventional	Organic	Conventional	Organic	Conventional
Go Early	80.06	79.22	39.87	41.49	93
Carberry	82.44	81.56	**36.83**	**41.49**	91
Glenn	84.11	83.89	37.30	38.53	90
CDC Titanium	82.03	81.21	**39.90**	**42.04**	96
Lillian	80.73	80.17	38.27	39.55	87
G-C	81.64	80.35	38.93	41.40	90
G-Gl	82.21	81.21	39.63	40.51	94
G-T	80.96	80.44	40.33	41.73	93
G-L	80.26	79.28	40.03	40.71	90
C-Gl	83.22	82.98	**38.7****	39.84	95
C-T	82.10	81.09	**39.8***	41.55	95
C-L	81.94	80.98	**37.83**	**40.22**	91
Gl-T	82.79	82.57	**38.73**	**41.18***	94
Gl-L	82.61	82.25	38.23	**40.24****	**95****
T-L	81.30	81.10	39.40	41.15	92
G-C-Gl	82.52	**80.88‡**	**37.90**	**40.29**	94
G-C-T	81.47	80.69	39.63	**40.87‡**	93
G-C-L	81.44	80.50	**39.87****	41.24	87
G-Gl-T	81.74	81.72	**40.10***	**41.64***	92
G-Gl-L	81.96	80.90	**39.93****	39.93	88
G-T-L	81.33	80.42	40.33	41.51	92
C-Gl-T	82.27	82.15	**39.23***	41.07	92
C-Gl-L	**83.07***	82.34	38.37	39.44	92
C-T-L	82.12	81.13	**39.47***	41.80	89
Gl-T-L	82.49	81.75	39.20	40.55	95
Mean	81.95	81.23	39.11	40.80	92
F values[b]					
Entry	***	***	***	***	*
Management	**ns**	**ns**	**ns**	**ns**	-
Entry * Management	**ns**	**ns**	**	**	-
SE (Entry)[c]	0.37	0.4	0.66	0.48	2.69
SE (Management)[d]	0.55	0.55	0.15	0.15	-
SE (Entry x Management)	0.63	0.63	0.82	0.82	-
LSD[e]	0.72	0.8	3.97	0.96	5.39

[a] *, ** Mixtures had significant greater than their mid-component averages at p≤0.05, 0.01 respectively. ‡ Mixtures had significant less than their mid-component averages at p≤0.05

[b] Letters indicate the significant difference between two management practices

[c] ns: not significant, *: significant at p≤0.05, **: significant at p≤0.01, ***: significant at p≤0.001

[d] Standard error of the difference between two least-square means.

[e] Standard error of the difference between conventional and organic management main effects.

[f] Least Significant Difference

Table 2.13 Least squares means of yield, height, maturity, and quality parameters of five cultivars and twenty two-way and three-way mixtures in combined environments from 2016 and 2017

Entry	Yield (t/ha)	Rank	AMMI stability value	Stability Rank	Height (cm)	Maturity (days)	Protein (%)	SDS sedimentation (mL)	Falling number (seconds)
Go Early	4.70[a]	19	0.10	1	96.33	94	13.78	29.43	385
Carberry	4.81	9	0.17	3	82.61	98	13.38	27.09	366
Glenn	4.60	21	0.48	18	89.71	100	14.05	29.32	358
CDC Titanium	5.16	1	0.44	16	91.22	94	13.86	27.18	412
Lillian	4.14	25	0.72	24	91.30	95	14.48	25.94	430
G-C	4.82	8	0.21	5	92.54	95	13.66	28.64	356
G-Gl	4.70	17	0.44	17	93.67	96	13.83	29.35	354
G-T	4.86	6	0.63	22	93.12	94	13.77	28.66	385
G-L	4.48	24	0.19	4	96.26	94	13.94	28.28	386
C-Gl	4.78	10	0.24	6	87.47	99	13.86	28.31	362
C-T	4.95	2	0.37	14	88.40	95	13.73	27.21	376
C-L	4.56	23	0.68	23	87.86	97	13.85	26.45	396
Gl-T	4.91	4	0.36	13	91.70	96	13.99	28.44	390
Gl-L	**4.7*** **	18	0.48	19	90.93	97	14.07	28.26	378
T-L	4.73	14	0.30	8	90.49	94	14.12	26.95	429
G-C-Gl	4.63	20	0.56	20	93.33	96	13.77	28.93	**339‡‡**
G-C-T	4.86	7	0.32	9	92.60	95	13.76	27.95	**357‡‡**
G-C-L	4.70	15	0.81	25	93.63	95	13.83	27.98	**355‡‡‡**
G-Gl-T	4.92	3	0.40	15	93.32	95	14.05	28.54	381
G-Gl-L	**4.7***	16	0.58	21	93.66	95	13.95	28.85	**366‡**
G-T-L	4.75	13	0.36	12	94.28	94	13.91	27.85	**376‡‡**
C-Gl-T	4.90	5	0.33	10	89.72	97	13.94	28.18	383
C-Gl-L	4.56	22	0.35	11	89.81	97	13.81	27.85	385
C-T-L	4.77	12	0.25	7	90.80	95	13.87	**27.73***	396
Gl-T-L	4.77	11	0.16	2	91.30	96	13.93	28.1	390
Mean	4.74				91.44	97	13.89	28.06	380
F values[b]									
Entry	***				***	***	***	***	***
SE[d]	0.11				0.86	0.7	0.14	0.47	13.11
LSD[e]	0.28				2.38	1.7	0.38	1.33	40.14

[a] *, *** Mixtures had significant greater than their mid-component averages at p≤0.05, 0.001 respectively. ‡, ‡‡, ‡‡‡ Mixtures had significant less than their mid-component averages at p≤0.05, 0.01, and 0.001 respectively

[c] ***: significant at p≤0.001

[d] Standard error of the difference between two least square means.

[e] Least Significant Difference

Table 2.14 Least squares means of heading, maturity, and yield of five cultivars and twenty two-way and three-way mixtures in Edmonton Conventional, Edmonton Organic, Beaverlodge, Lethbridge, and Kernen from 2016 and 2017

Entry	Edmonton Conventional		Edmonton Organic		Beaverlodge			Lethbridge			Kernen		
	Heading (days)	Maturity (days)	Heading (days)	Maturity (days)	Yield (t/ha)	Rank	Maturity (days)	Yield (t/ha)	Rank	Maturity (days)	Yield (t/ha)	Rank	Maturity (days)
Go Early	60	94	50	86	4.70[a]	15	106	4.09	13	99	4.78	21	89
Carberry	59	101	49	88	4.94	7	115	4.06	15	102	4.96	10	93
Glenn	60	108	50	89	4.28	23	114	3.86	23	103	4.73	23	91
CDC Titanium	59	96	49	86	5.30	1	107	4.87	1	99	5.11	2	89
Lillian	65	98	53	85	4.02	25	109	4.17	9	100	4.38	25	89
G-C	60	98	49	87	4.51	18	108	4.20	6	101	4.99	8	90
G-Gl	59	96	50	87	4.30	22	110	4.12	11	102	4.81	20	90
G-T	61	95	49	85	**4.36 ‡**	21	106	4.32	4	99	5.03	5	88
G-L	63	95	51	85	4.39	20	107	4.11	12	100	4.61	24	89
C-Gl	60	101	50	89	4.61	17	114	4.02	18	104	4.89	14	91
C-T	60	98	50	87	4.97	6	111	4.41	3	100	5.14	1	90
C-L	62	99	53	88	4.99	3	114	3.91	21	101	**4.84***	17	91
Gl-T	59	100	48	87	4.99	5	111	4.42	2	103	5.01	6	90
Gl-L	60	98	52	88	**4.84***	12	113	3.97	19	101	**4.91*****	13	92
T-L	60	96	52	85	4.99	4	107	4.20	7	100	**4.93****	12	89
G-C-Gl	61	98	50	88	4.18	24	111	3.92	20	101	4.86	16	90
G-C-T	60	96	50	87	4.78	13	109	**3.84 ‡**	24	99	5.06	3	89
G-C-L	63	95	52	86	4.89	9	110	3.80	25	98	**4.87****	15	90
G-Gl-T	61	97	49	87	4.86	10	109	4.07	14	100	4.99	9	90
G-Gl-L	62	97	50	86	**5.04***	2	110	4.30	5	100	**4.82****	19	90
G-T-L	60	96	50	86	4.62	16	107	4.19	8	100	4.84	18	89
C-Gl-T	60	100	50	88	4.85	11	111	4.03	16	100	5.04	4	90
C-Gl-L	60	102	51	87	4.42	19	112	3.88	22	102	4.75	22	90
C-T-L	61	99	51	86	4.74	14	111	4.02	17	100	**5 ****	7	90
Gl-T-L	60	99	52	86	4.89	8	112	4.15	10	100	**4.93****	11	89
Mean	60	98	50	87	4.77		110	4.12		101	4.89		90
F values[c]													
Entry	***	***	***	***	**ns**		***	*		***	***		***
SE[d]	1.21	1.72	0.67	0.89	0.36		1.23	0.25		0.88	0.08		0.73
LSD[e]	2.56	3.4	1.33	1.84	0.71		2.56	0.65		1.8	0.17		1.44

[a] *, **, *** Mixtures had significant greater than their mid-component averages at p≤0.05, 0.01, 0.001 respectively. ‡ Mixtures had significant less than their mid-component aver ages at p≤0.05, 0.01, and 0.001 respectively

[c] ns: not significant, *: significant at p≤0.05, ***: significant at p≤0.001

[d] Standard error of the difference between two least square means.

[e] Least Significant Difference

Table 2.15 Least squares means of test weight (TW), thousand kernel weight (TKW), and grain protein of five cultivars and twenty two-way and three-way mixtures in Certified Organic, Beaverlodge, Lethbridge, and Kernen from 2016 to 2017

Entry	Certified Organic			Bevaerlodge	Lethbridge	Kernen
	TW (kg/hL)	TKW (g)	Protein (%)	Protein (%)	Protein (%)	Protein (%)
Go Early	73.95[a]	32.13	12.41	12.92	14.53	13.71
Carberry	78.95	37.20	10.81	13.32	14.01	13.63
Glenn	81.26	35.73	11.39	14.33	14.47	13.93
CDC Titanium	78.10	36.27	12.07	13.61	14.13	14.29
Lillian	77.65	40.07	11.74	14.20	14.82	14.33
G-C	75.37	34.47	11.79	13.20	14.22	13.81
G-Gl	77.52	34.13	11.71	13.60	14.36	13.71
G-T	74.90	33.67	12.27	13.43	14.39	13.69
G-L	75.40	**34.73**‡	12.16	13.43	14.65	13.91
C-Gl	79.18	35.73	11.33	13.85	14.21	13.69
C-T	79.16	36.60	11.29	13.49	14.35	13.98
C-L	77.36	**36.8**‡‡	11.47	13.84	14.39	13.73
Gl-T	78.66	35.86	11.36	13.94	14.00	14.14
Gl-L	79.53	**36.13**‡‡	11.47	13.95	14.26	13.79
T-L	78.75	37.53	12.15	13.76	14.39	14.28
G-C-Gl	76.75	34.00	11.54	13.51	14.36	13.77
G-C-T	77.09	34.60	11.65	13.42	14.29	13.84
G-C-L	75.34	36.13	11.43	13.21	14.41	13.78
G-Gl-T	77.19	34.86	12.07	13.63	14.84	13.93
G-Gl-L	78.25	35.6	11.82	13.69	14.37	13.84
G-T-L	76.35	35.07	12.04	13.51	14.15	14.00
C-Gl-T	79.02	36.00	11.72	13.93	14.26	13.79
C-Gl-L	79.39	37.27	11.50	13.71	14.58	13.71
C-T-L	78.40	37.00	11.43	13.60	14.29	13.98
Gl-T-L	78.73	**36.07**‡	11.93	14.13	14.27	**13.73**‡
Mean	77.69	35.75	11.71	13.65	14.36	13.88
F values[b]						
Entry	***	***	***	***	**ns**	**Ns**
SE[c]	0.92	0.72	0.26	0.23	0.3	0.25
LSD[d]	1.85	1.45	0.52	0.483	0.62	0.51

[a] ‡, ‡‡ Mixtures had significant less than their mid-component averages at p≤0.05 and 0.01 respectively
[c] ns: not significant, *: significant at p≤0.05, ***: significant at p≤0.001
[d] Standard error of the difference between two least square means.
[e] Least Significant Difference

Table 2.16 Least squares means of the number of tillers, height, and lodging rate of five cultivars and twenty two-way and three-way mixtures in Certified Organic, Beaverlodge, Lethbridge, and Kernen from 2016 to 2017

Entry	Certified Organic			Beaverlodge		Lethbridge	Kernen	
	Number of tillers (m^{-2})	Height (cm)	Lodging rate (1-9)	Height (cm)	Lodging rate (1-9)	Height (cm)	Height (cm)	Lodging rate (1-9)
Go Early	707[a]	96.47	6.3	98.50	7.0	85.67	101.83	2.8
Carberry	909	80.63	1.0	82.33	5.7	74.33	87.83	1.0
Glenn	893	95.33	2.0	86.00	5.0	77.33	94.33	1.5
CDC Titanium	1045	92.47	5.3	90.50	8.3	82.00	96.67	3.5
Lillian	699	93.97	2.0	86.33	6.3	80.33	99.83	4.5
G-C	797	92.10	2.7	91.83	5.3	85.67	100.67	1.7
G-Gl	725	96.67	3.3	90.67	5.3	82.00	101.17	1.7
G-T	755	95.53	6.3	92.83	**6.3‡**	81.67	101.17	2.7
G-L	787	96.83	6.0	96.50	6.7	92.33	100.83	3.2
C-Gl	824	90.17	1.7	87.17	5.0	75.67	92.83	1.0
C-T	**677‡‡‡**	88.03	**6.3****	88.33	7.0	77.00	95.33	1.5
C-L	832	89.93	1.0	87.67	7.0	78.33	94.33	**1.5‡‡**
Gl-T	992	93.13	4.3	93.00	6.7	82.33	97.67	2.17
Gl-L	875	90.70	2.0	91.50	**7***	80.67	94.67	**1.8‡‡**
T-L	760	92.27	3.0	86.00	7.7	83.33	96.17	3.7
G-C-Gl	859	97.57	4.3	93.67	5.7	83.67	100.17	1.7
G-C-T	859	96.60	5.0	89.83	6.3	83.33	98.33	**1.5‡**
G-C-L	779	94.17	4.0	90.17	6.3	88.67	101.67	**1.5‡‡‡**
G-Gl-T	747	96.07	4.7	89.50	7.3	84.67	100.00	**1.67‡**
G-Gl-L	883	98.53	5.0	93.17	5.0	83.33	98.00	2.5
G-T-L	797	95.17	3.7	94.33	6.7	82.67	101.83	2.8
C-Gl-T	1059	89.77	4.3	87.83	6.3	78.33	95.67	1.3
C-Gl-L	779	92.50	1.3	92.00	5.3	77.33	93.83	**1.5‡**
C-T-L	907	92.20	3.0	88.83	7.3	83.00	97.17	**1.5‡‡‡**
Gl-T-L	848	95.80	1.7	90.00	6.3	79.67	98.17	**2.2‡‡**
Mean	832	93.30	3.6	90.34	6.4	81.73	97.61	2.09
F values[b]								
Entry	**	***	***	***	**	***	***	***
SE[c]	95.11	2.19	1.18	3.26	0.75	2.09	1.67	0.46
LSD[d]	191	4.4	2.38	6.53	1.51	4.11	3.42	0.9

[a] *, ** Mixtures had significant greater than their mid-component averages at p≤0.05 and 0.01 respectively. ‡, ‡‡, ‡‡‡ Mixtures had significant less than their mid-component averages at p≤0.05, 0.01, and 0.001 respectively

[c] **: significant at p≤0.01, ***: significant at p≤0.001

[d] Standard error of the difference between two least square means.

[e] Least Significant Difference

Table 2.17 Least square means of SDS sedimentation and falling number of five cultivars and twenty two-way and three-way mixtures in Certified Organic, Beaverlogde, Lethbridge, and Kernen from 2016 to 2017

Entry	Certified Organic		Beaverlodge		Lethbridge		Kernen	
	SDS sedimentation (mL)	Falling number (seconds)	SDS sedimentation (mL)	Falling number (seconds)	SDS sedimentation (mL)	Falling number (seconds)	SDS Sedimentation (mL)	Falling number (seconds)
Go Early	26.67[a]	515	32.68	269	31.85	429	31.49	416
Carberry	25.21	386	31.09	274	29.15	393	28.32	391
Glenn	23.63	438	33.47	276	30.83	417	30.70	417
CDC Titanium	24.02	491	31.75	334	28.29	391	29.64	455
Lillian	19.93	456	29.24	338	30.10	454	26.67	454
G-C	25.21	404	**33.6***	253	30.96	399	29.17	383
G-Gl	25.87	**357‡‡‡**	33.34	239	31.03	424	31.55	403
G-T	**27.33***	502	32.81	261	31.43	370	30.30	447
G-L	24.55	445	**32.61***	**260‡**	**28.02‡**	461	29.83	435
C-Gl	24.16	398	32.28	271	29.87	416	29.50	422
C-T	24.95	397	31.09	293	28.75	392	28.85	422
C-L	22.57	391	29.57	273	28.75	453	27.13	457
Gl-T	23.37	430	33.27	309	29.67	425	29.97	424
Gl-L	**24.29***	397	32.08	288	29.34	405	29.18	456
T-L	**23.89***	511	31.56	326	28.22	424	28.51	470
G-C-Gl	25.74	**338‡‡‡**	33.07	271	31.16	357	29.64	396
G-C-T	24.82	412	32.81	259	29.05	350	29.37	402
G-C-L	23.89	420	32.02	254	30.20	363	28.91	420
G-Gl-T	25.48	450	32.61	278	29.41	395	30.43	440
G-Gl-L	23.90	415	32.48	287	31.42	378	29.84	396
G-T-L	24.16	**401‡‡**	**32.88***	**273‡**	30.33	395	29.11	437
C-Gl-T	24.29	422	**33.47***	**251‡**	29.47	448	29.31	415
C-Gl-L	23.63	447	32.02	275	29.90	417	29.37	440
C-T-L	24.29	414	31.16	319	29.57	390	28.64	433
Gl-T-L	23.37	471	**32.94***	279	30.30	396	29.11	448
Mean	24.37	428	32.24	280	29.88	406	29.38	427
F values[b]								
Entry	***	***	***	**	**ns**	**ns**	*	*
SE[c]	1.09	37.54	0.78	24.88	1.27	41.17	1.08	21.33
LSD[d]	2.19	75.39	1.6	50.52	2.63	84.98	2.24	44.02

[a] * Mixtures had significant greater than their mid-component averages at p≤0.05. ‡, ‡‡, ‡‡‡ Mixtures had significant less than their mid-component averages at p≤0.05, 0.01, and 0.001 respectively

[c] ns: not significant, *: significant at p≤0.05, **: significant at p≤0.01, ***: significant at p≤0.001

[d] Standard error of the difference between two least square means.

[e] Least Significant Difference

Table 2.18 Pearson's coefficients of correlation (p≤0.05) between grain yield and other agronomic traits for twenty five entries at four conventional locations from 2016 to 2017.

	Location	Heading	Maturity	Height	Tillers	LI	Lodging rate	Protein
Yield	Beaverlodge		**0.18***	**0.26****				-
	Edmonton Conventional	-[a]	-	**-0.26****	-	**0.19***	**-0.39*****	-
	Kernen		**-0.32*****	0.18*			**-0.29*****	
	Lethbridge		**-0.73*****	**-0.28*****				

[a] Correlation coefficient not significant (p>0.05)

Table 2.19 Pearson's coefficients of correlation (p≤0.05) between grain yield, weed biomass, and other agronomic traits for twenty five entries at Edmonton Organic from 2016 to 2017

	Heading	Maturity	Height	Tillers	Yield	Protein	Weed biomass
Yield	**-0.39*****	-[a]	-	**0.32*****		**0.4*****	**-0.5*****
Weed biomass	**0.76*****	**0.55*****	**0.4*****	**-0.35*****	**-0.5*****	**-0.66*****	

[a] Correlation coefficient not significant (p>0.05)

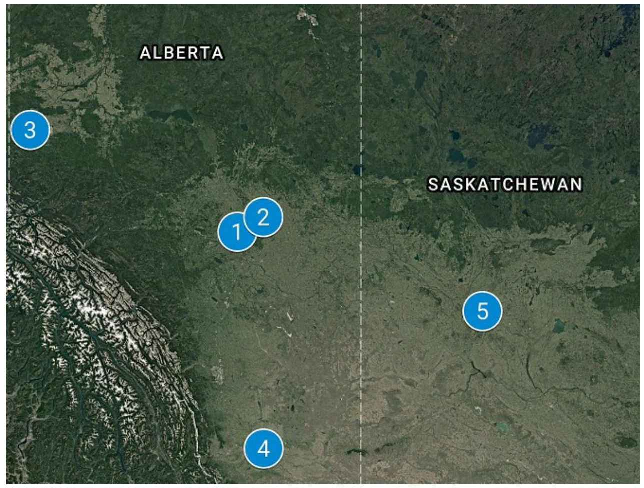

Figure 2.1. Locations of experimental sites in Alberta and Saskatchewan province. 1) Edmonton Research Station including Edmonton Conventional and Edmonton Organic 2) Certified Organic farm. 3) Beaverlodge Research Farm. 4) Lethbridge Research and Development Centre. 5) Kernen Research Farm. (Source: Google Map).

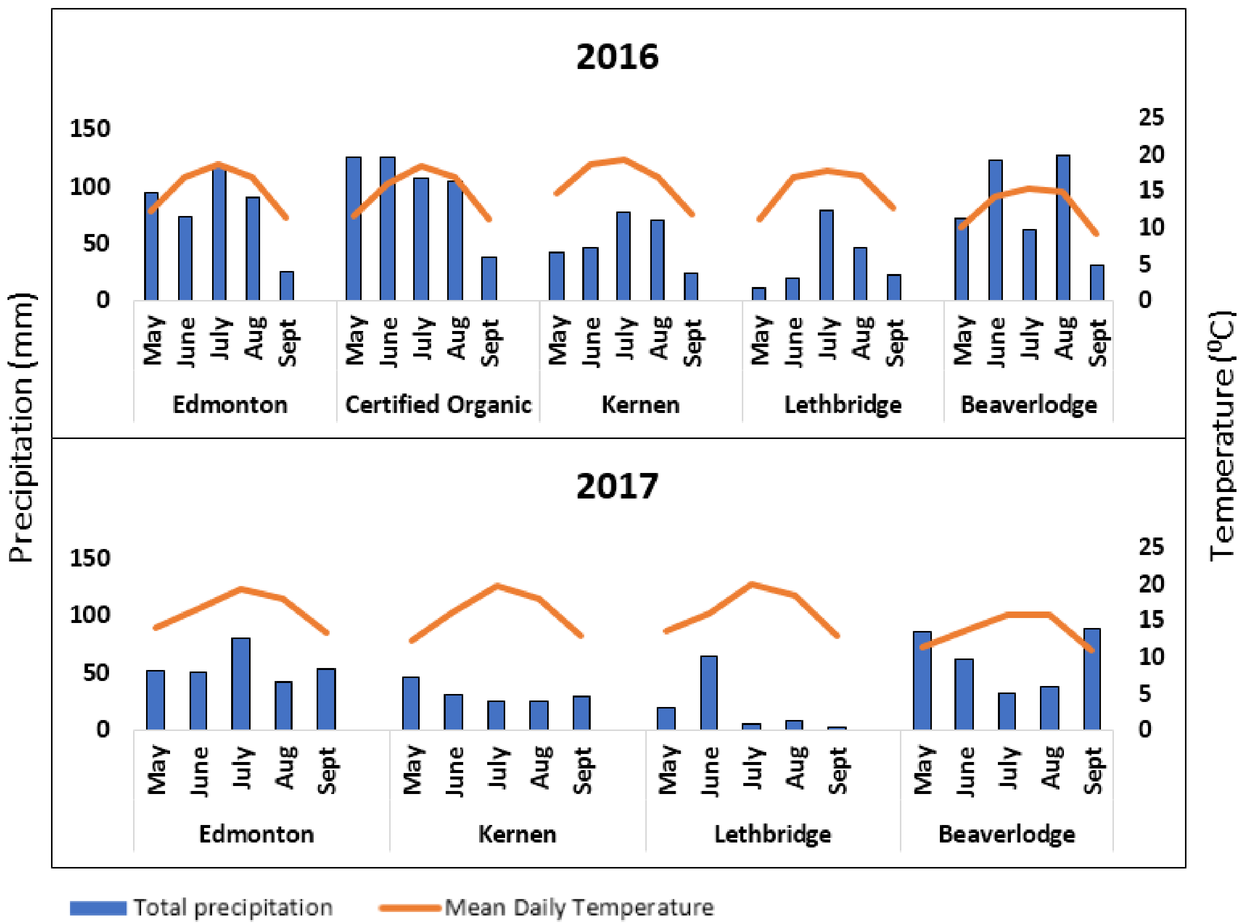

Figure 2.2 Weather data contains monthly precipitation and average daily temperature at tested locations. Data obtained from Government of Canada and Alberta Agriculture and Forestry.

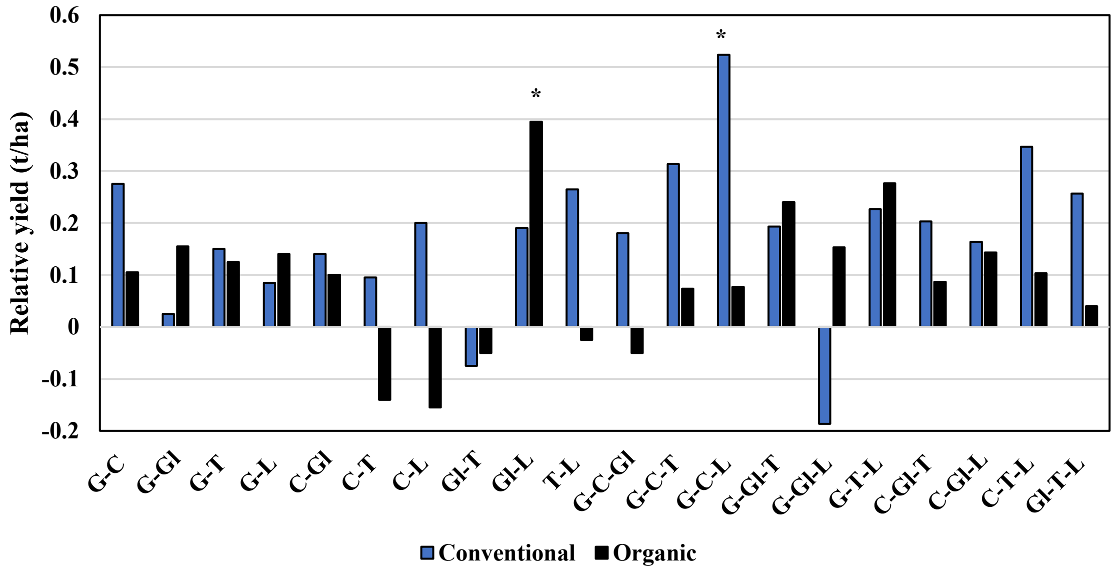

Figure 2.3 Relative yield (RY) of each mixture under conventional and organic environments in Edmonton. * indicates the significant different of RY from 0 at p≤0.05.

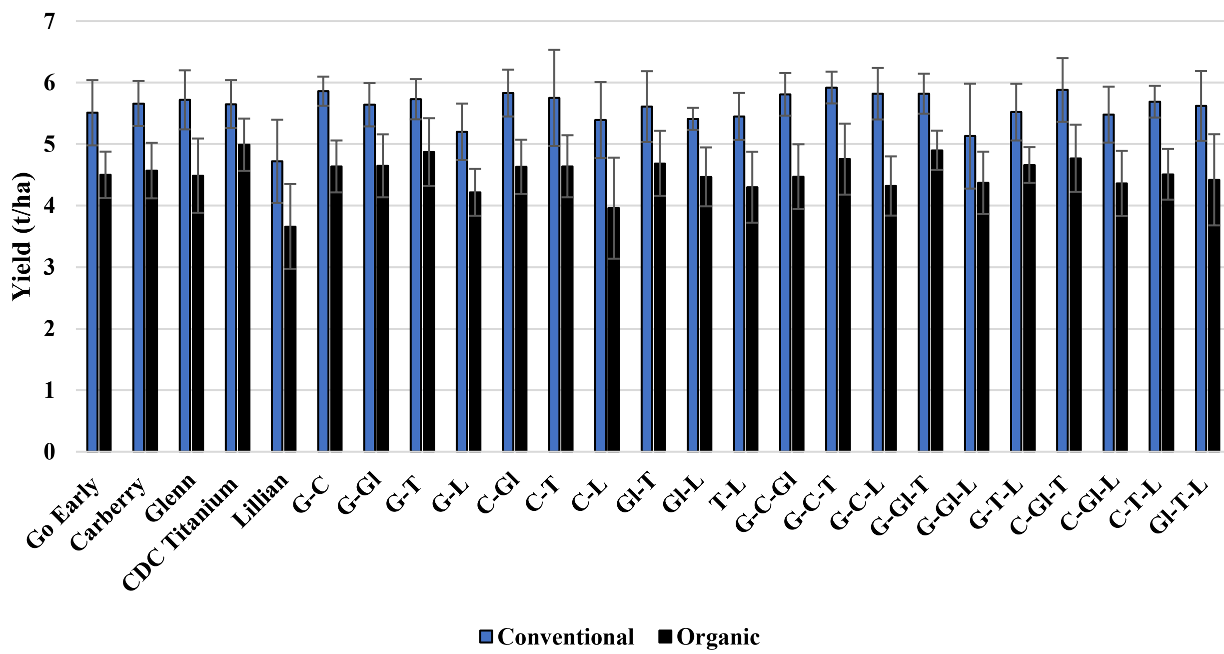

Figure 2.4 Grain yield of five cultivars and twenty two-way and three-way mixtures under conventional and organic environments in Edmonton from 2016 to 2017. Bars represent standard deviation of the mean.

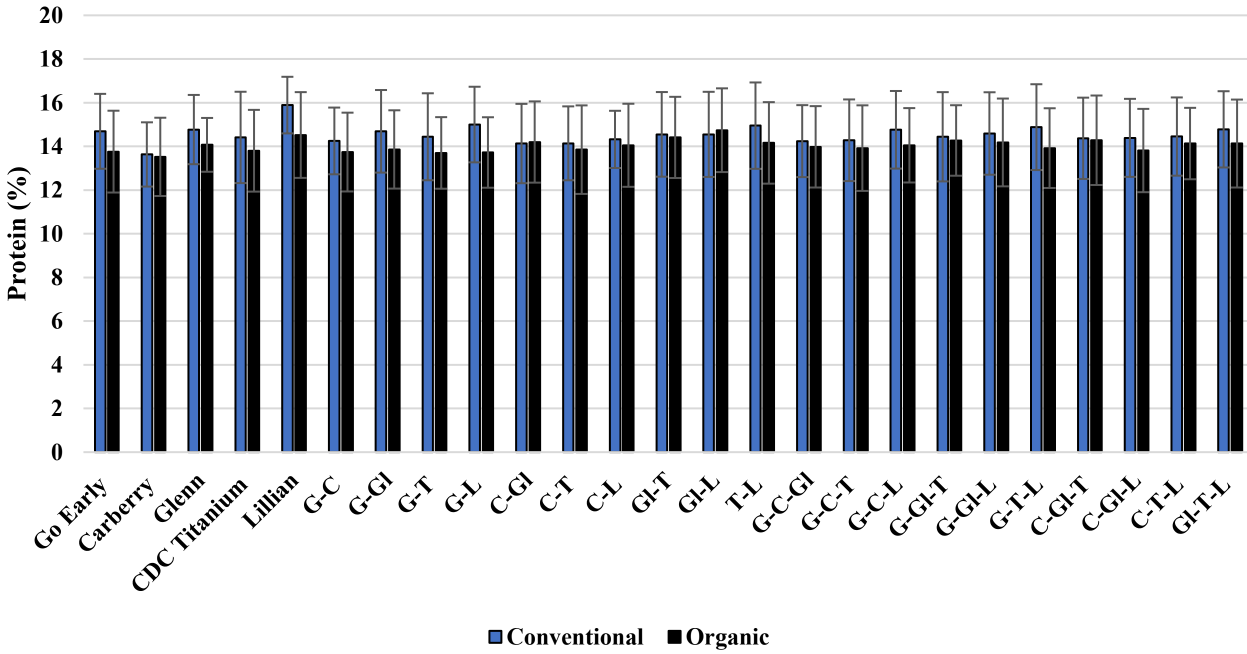

Figure 2.5 Grain protein content of five cultivars and twenty two-way and three-way mixtures under conventional and organic environments in Edmonton from 2016 to 2017. Bars represent standard deviation of the mean.

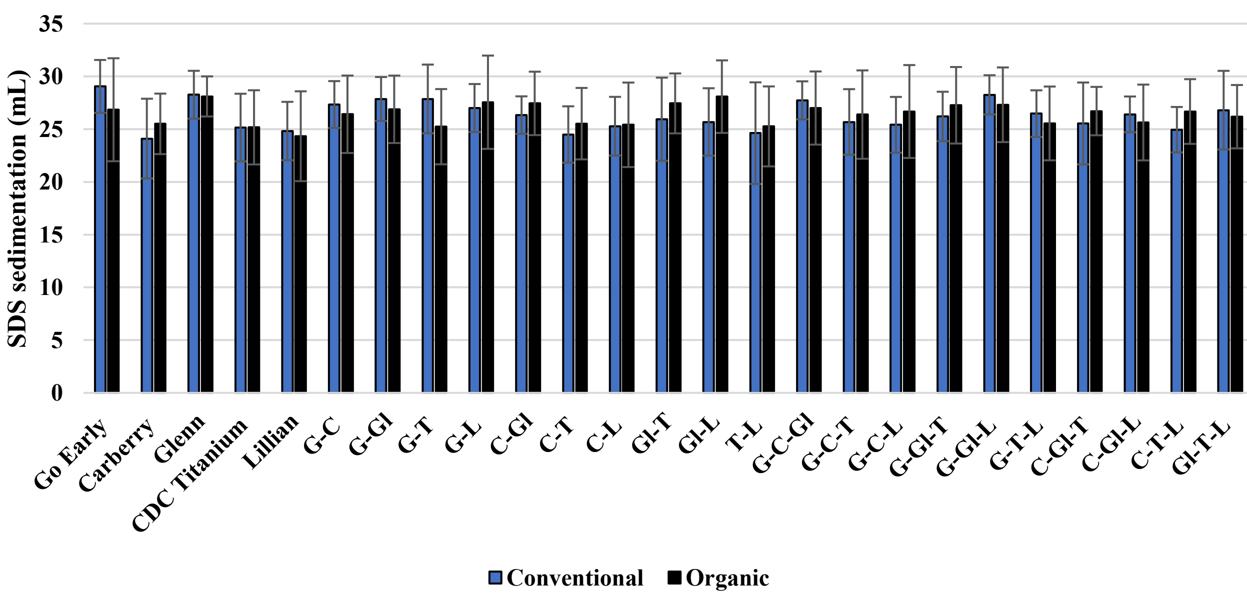

Figure 2.6 SDS sedimentation of five cultivars and twenty two-way and three-way mixtures under conventional and organic environments in Edmonton from 2016 to 2017. Bars represent standard deviation of the mean.

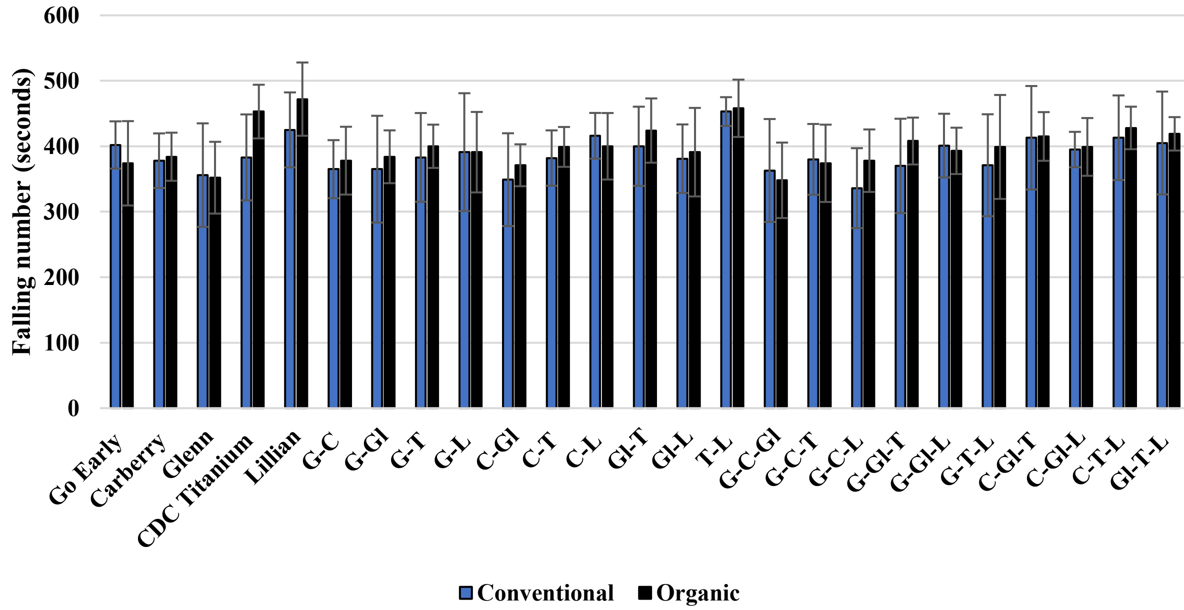

Figure 2.7 Falling number of five cultivars and twenty two-way and three-way mixtures under conventional and organic environments in Edmonton from 2016 to 2017. Bars represent standard deviation of the mean.

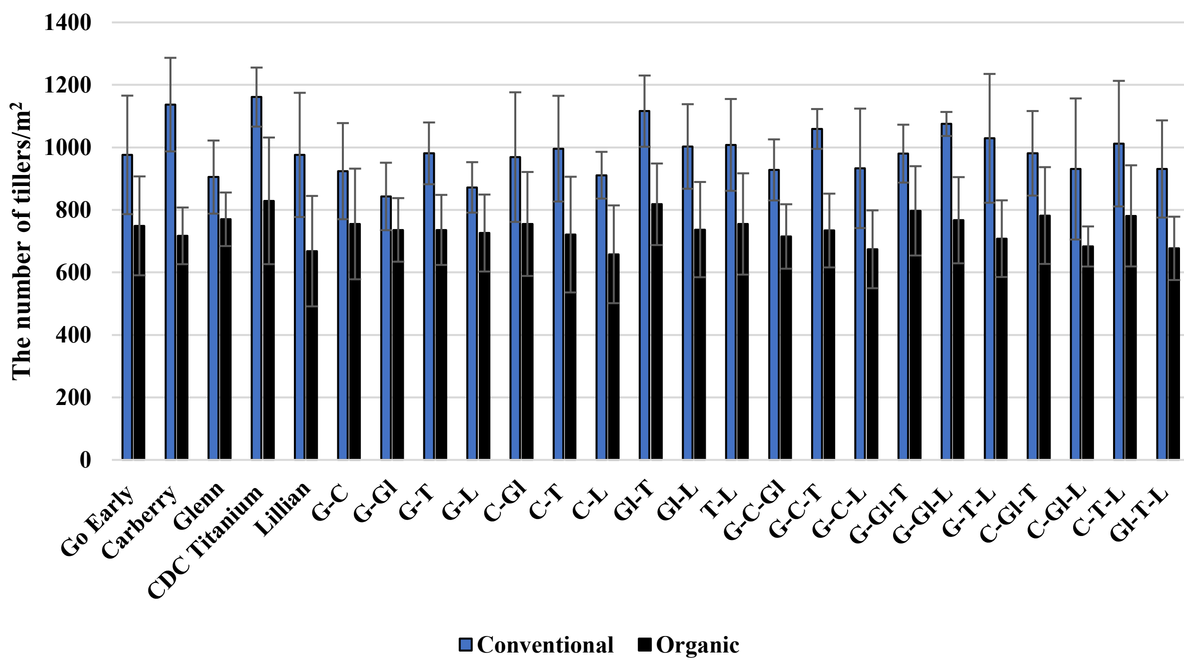

Figure 2.8 The number of tillers of five cultivars and twenty two-way and three-way mixtures under conventional and organic environments in Edmonton from 2016 to 2017. Bars represent standard deviation of the mean.

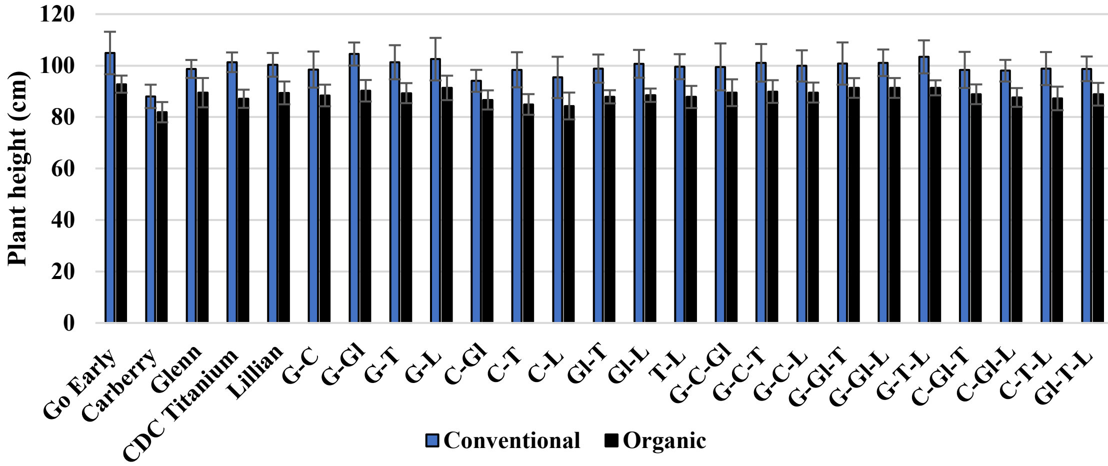

Figure 2.9 Plant height of five cultivars and twenty two-way and three-way mixtures under conventional and organic environments in Edmonton from 2016 to 2017. Bars represent standard deviation of the mean.

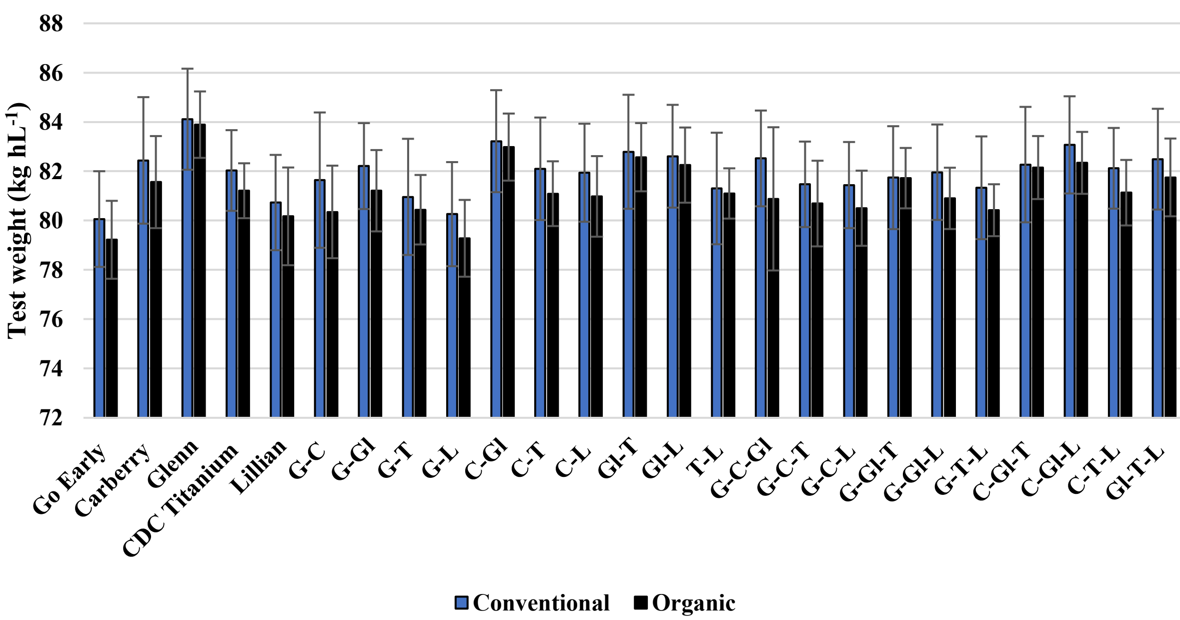

Figure 2.10 Test weight of five cultivars and twenty two-way and three-way mixtures under conventional and organic environments in Edmonton from 2016 to 2017. Bars represent standard deviation of the mean.

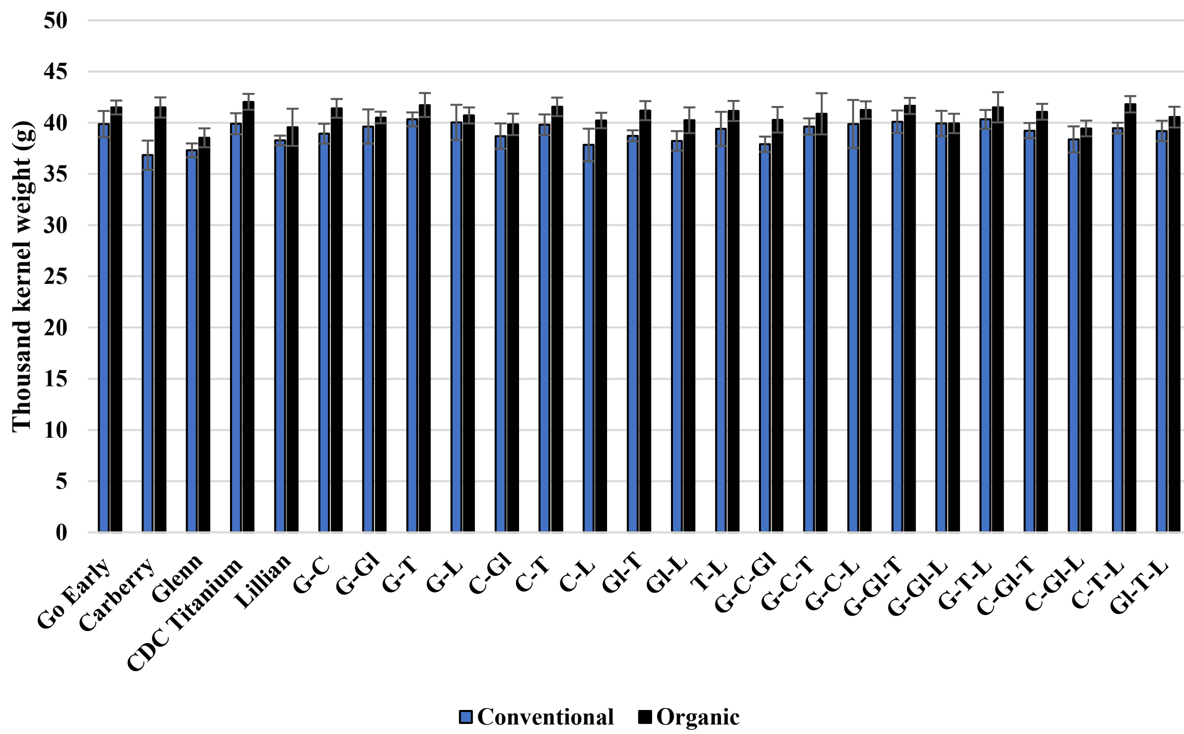

Figure 2.11 Thousand kernel weight of five cultivars and twenty two-way and three-way mixtures under conventional and organic environments in Edmonton from 2016 to 2017. Bars represent standard deviation of the mean.

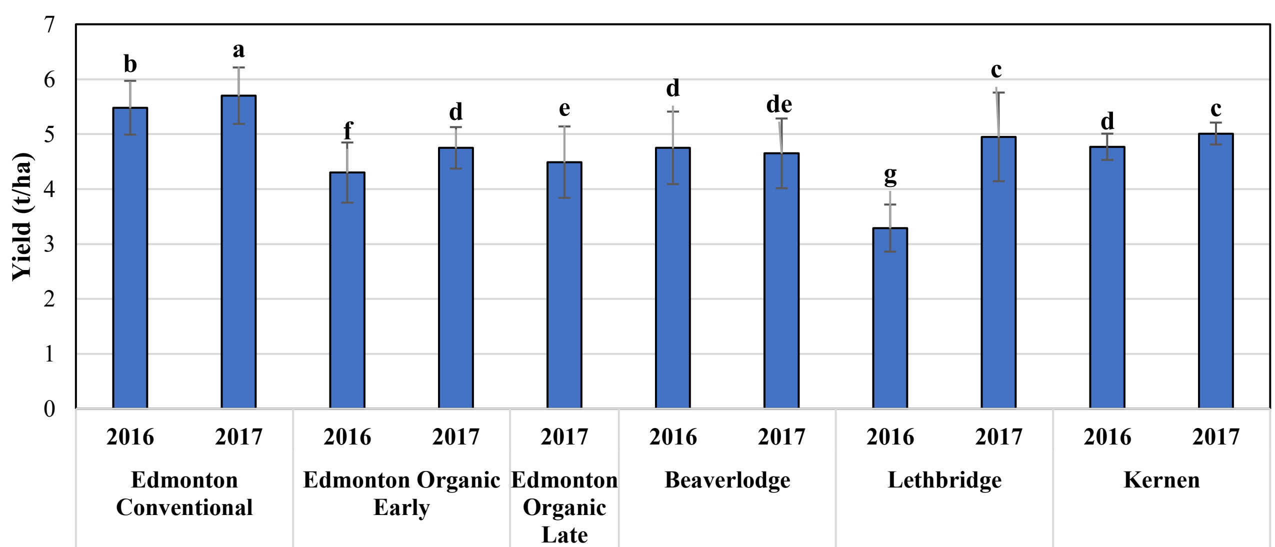

Figure 2.12 The mean grain yield of each environment from 2016 to 2017. Letters indicate the significant difference at p≤0.001. Bars represent standard deviation of the mean.

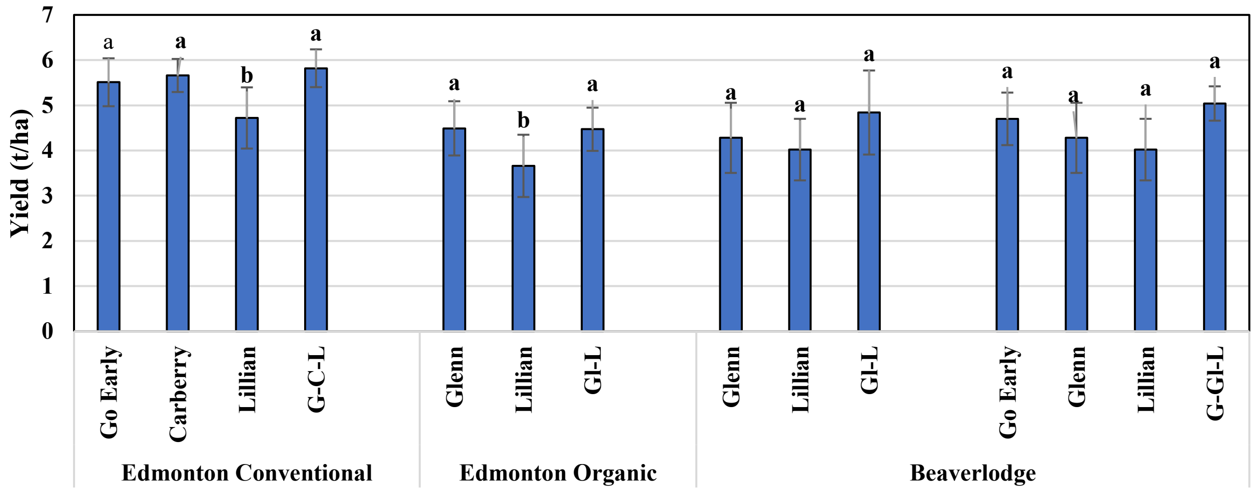

Figure 2.13 Grain yield of wheat cultivars and their mixtures at Edmonton Conventional, Edmonton Organic, and Beaverlodge. Letters indicate the significant difference at p≤0.05. Bars represent standard deviation of the mean.

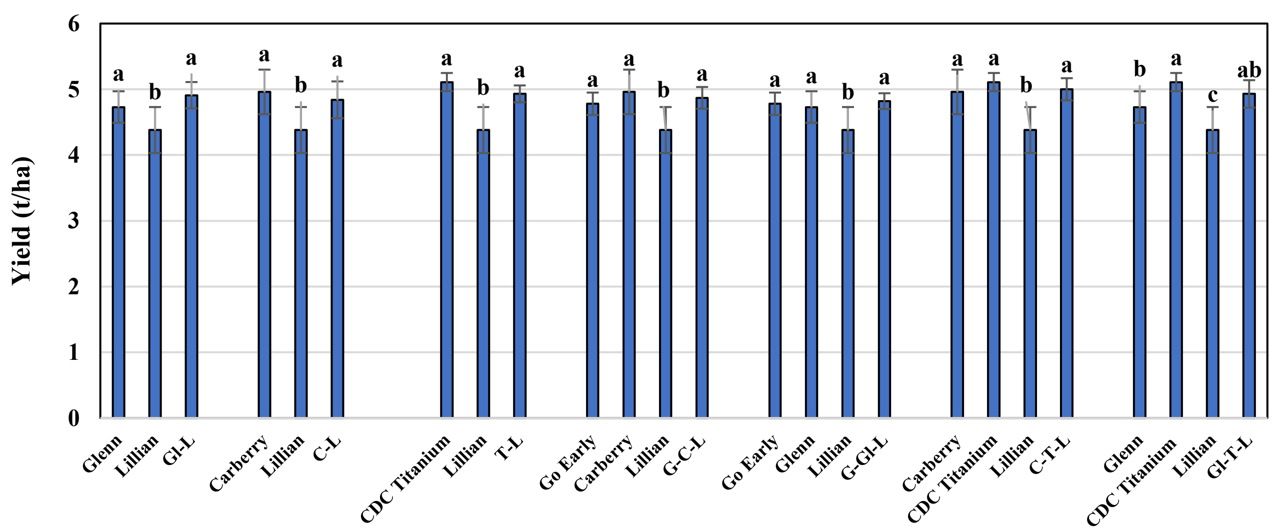

Figure 2.14 Grain yield of wheat cultivars and their mixtures at Kernen. Letters indicate the significant difference at p≤0.05. Bars represent standard deviation of the mean.

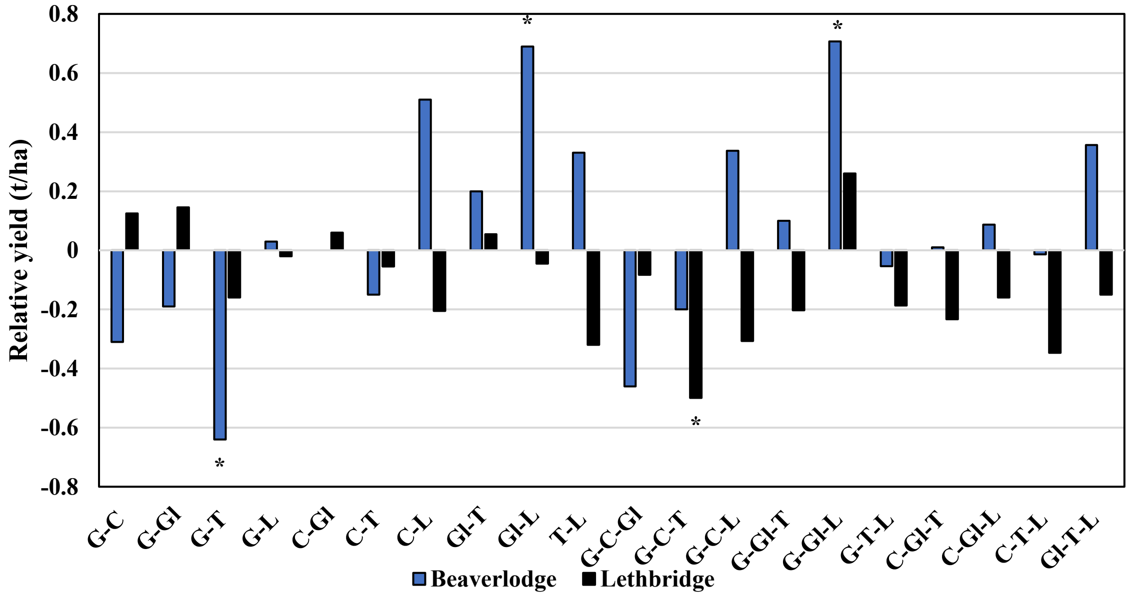

Figure 2.15 Relative yield (RY) of each mixture at Beaverlodge and Lethbridge. * indicates the significant different of RY from 0 at p≤0.05.

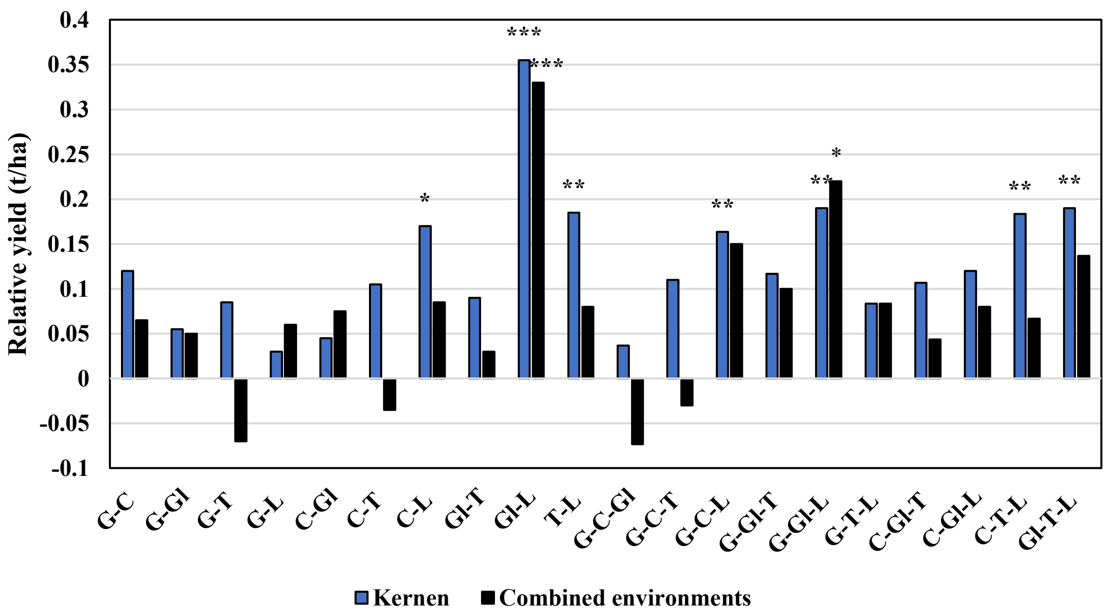

Figure 2.16 Relative yield (RY) of each mixture at Kenen and combined environments. *, **, *** indicates the significant different of RY from 0 at p≤0.05, 0.01, and 0.001 respectively.

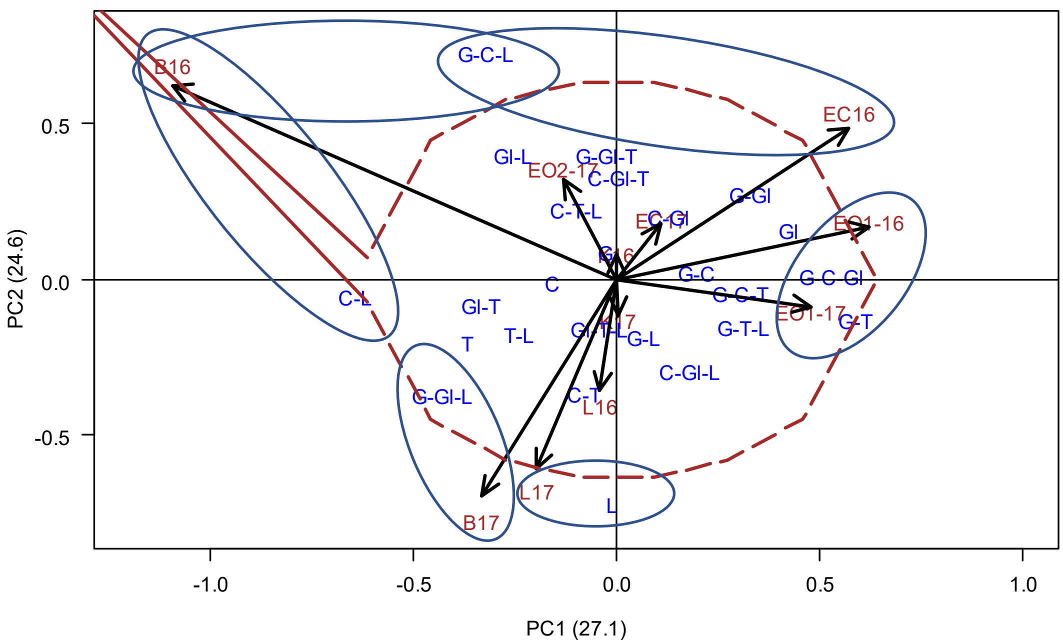

Figure 2.17. Biplot graph of mean yield of five CWRS cultivars and twenty two-way and three-way mixtures in eleven environments (combination of year and location) under organic and conventional management in western Canada (EC16: Edmonton Conventional 2016, EC17: Edmonton Conventional 2017, EO1-16: Edmonton Organic Early 2016, EO1-17: Edmonton Organic Early 2017, EO2-17: Edmonton Organic Late 2017, B16: Beaverlodge 2016, B17: Beaverlodge 2017, L16: Lethbridge 2016, L17: Lethbridge 2017, K16: Kernen 2016, K17: Kernen 2017). See Table 2.1 for abbreviated from of entries. Cultivars and mixtures at the vertices of the contour line are the most responsive entries, while the circle represents the positive interaction between environments and entries.

3.1 General Discussion and Conclusions

The majority of food has come from conventional agriculture. However, the negative impacts of that production approach have been confirmed by the academic works, gaining the attention towards a more sustainable approach. Organic agriculture emphasizing harmony rather than against the nature has the potential to fill that urgent demand.

Wheat has been serving the global population, making up one of the highest land use and production. This grain crop also represents the vital role in conventional and organic production in Canada, especially Western Canada. However, wheat performance is totally different between conventionally and organically managed systems because of the difference in agronomic practices and natural conditions. Therefore, research targeting both environments are necessary.

Wheat cultivar mixtures have been employed to benefit both conventional and organic agriculture. Since wheat cultivar mixtures could stabilize yield under the variability of climate, improve yield, manage diseases and pests. Recent findings have also explored the benefits of wheat cultivar mixtures on quality enhancement, weed control, and abiotic resistances. Developing guidelines for successful mixture in both conventional and organic environment formed the basis of this thesis, with the following objectives:

1. To evaluate yield performance of components and wheat cultivar mixtures grown under conventional and organic conditions.

2. To evaluate the grain quality of components and wheat cultivar mixtures grown under conventional and organic conditions.

3. To compare weed suppression of components with wheat cultivar mixtures grown under organic condition.

4. To compare the degree of lodging resistance of components with wheat cultivar mixtures under conventional and organic conditions.

The following are summary points from the previous chapter developed from these objectives:

The performance of spring wheat (*Triticum aestivum* L.) cultivar mixtures in organically and conventionally managed systems in western Canada

- Grain yield of both cultivars and spring wheat cultivar mixtures was lower under the organically than that under the conventionally managed system in north central Alberta. In the conventional system, the mixture of Go Early (tall)-Carberry (semi-dwarf)-Lillian (medium) increased yield compared to it midcomponent in the presence of lodging incidence. In the organic system, the mixture of Glenn (early heading, late maturity) and Lillian (late heading, medium maturity) improved yield compared to it midcomponent. Across the environments in western Canada, the mixture Glenn (early heading, late maturity, lodging resistance)-CDC Titanium (early heading, early maturity, wheat midge resistance)-Lillian (late heading, medium maturity, wheat stem sawfly resistance) was both stable and productive. Mixtures Glenn-Lillian and Go Early-Glenn-Lillian improved yield compared to their midcomponents in western Canada.
- Grain protein content of both cultivars and mixtures decreased, while gluten was stronger in some mixtures (Gl-T, Gl-L) in the organic system in north central Alberta. Comparing to the midcomponent, the organic mixture of Carberry-Glenn enhanced protein content, while the organic mixture of Glenn-Lillian strengthened gluten quality. Mixing weak-gluten cultivar with strong-gluten cultivars enhanced the overall gluten quality.
- No difference in weed suppression between wheat cultivar mixtures and their components in the organic system in north central Alberta. The reference for mixing is to include early-heading and high-tillering cultivars in order to maintain sufficient yield under weedy environments.
- Semi-dwarf and strong-stem cultivars (Carberry and Glenn) resisted lodging better than other cultivars (Go Early, CDC Titanium, and Lillian) in conventional systems in north central Alberta, northwest Alberta, and central Saskatchewan. Wheat cultivar mixtures including lodging-resistant cultivars also reduced lodging damage compared to their respective components under conventionally managed systems. That benefit contributed to improved yield.

3.2 Recommendation for Future Research

Up to seven wheat cultivar mixtures in central Saskatchewan yielded better than their respective components. That could be attributed to favorable growing conditions for mixtures' performance. A study testing more mixtures including new cultivars under that environment would be critical to validate the previous hypothesis, and subsequently inform farmers the productivity of mixtures could be achieved in that area. In the contrast, mixtures showed no significant yield increase in south Alberta, which is likely due to low precipitation in two years. Thus, another study evaluating water use efficiency of wheat cultivar mixtures and determining the contributing agronomic factors would be crucial under drought conditions, generally western Canada which is predicted to be drier and warmer in the future. In this study, yield benefit and high protein content could be achieved by organic wheat cultivar mixtures having complementary traits in these properties. Other nutritional aspects such as Ca, Cu, Fe, Mg, Mn, P, Zn are also worth consideration, suggesting a study on enhancing these minerals and improving yield simultaneously under low-input environment. Finally, the current study only ended up finding out the advantages of wheat cultivars mixtures on yield, milling, and baking qualities. A comparative study on comparing products made from flour of mixtures and the common flour would be vital to confirm the commercial values of mixtures. That would give industrial producers and artisanal bakers the confidence to employ mixture flour into their wheat-based products, especially bread.

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4.1 Appendices

Appendix 4.1 Two-way G x E table for yield ($t\ ha^{-1}$) of five sole cultivars and twenty two-way and three-way mixtures across eleven environments

Entry	Edmonton Conventional 2016	Edmonton Conventional 2017	Edmonton Organic 1 2016	Edmonton Organic 1 2017	Edmonton Organic 2 2017	Beaverlodge 2016	Beaverlodge 2017	Lethbridge 2016	Lethbridge 2017	Kernen 2016	Kernen 2017	**Mean**	Mid-component average[a]
Go Early	5.44[a]	5.58	4.55	4.54	4.42	4.87	4.52	3.21	4.97	4.66	4.90	**4.70**	-
Carberry	5.53	5.79	4.24	4.70	4.76	4.92	4.96	3.00	5.11	4.70	5.21	**4.81**	-
Glenn	5.89	5.56	4.25	4.93	4.28	4.30	4.26	3.10	4.62	4.53	4.94	**4.61**	-
CDC Titanium	5.31	5.98	4.90	4.88	5.20	5.45	5.13	3.84	5.90	5.01	5.22	**5.17**	-
Lillian	4.57	4.87	3.40	4.44	3.15	3.86	4.18	3.41	4.93	4.06	4.69	**4.14**	-
G-C	5.72	6.01	4.33	4.97	4.61	4.57	4.44	2.96	5.44	4.94	5.05	**4.82**	4.75
G-Gl	5.86	5.43	4.67	4.76	4.51	4.62	3.98	3.17	5.08	4.67	4.94	**4.70**	4.65
G-T	5.60	5.86	5.18	4.94	4.50	4.15	4.57	3.62	5.02	4.95	5.11	**4.86**	4.93
G-L	5.55	4.85	4.17	4.13	4.35	4.25	4.53	3.24	4.99	4.48	4.75	**4.48**	4.42
C-Gl	5.63	6.02	4.45	4.90	4.55	4.80	4.41	3.01	5.03	4.76	5.03	**4.78**	4.71
C-T	5.20	6.30	4.47	4.98	4.47	4.78	5.16	3.32	5.49	5.01	5.27	**4.95**	4.99
C-L	5.06	5.73	3.39	4.38	4.12	5.23	4.75	2.76	5.05	4.64	5.04	**4.56**	4.48
Gl-T	5.09	6.12	4.19	4.95	4.92	5.16	4.79	3.55	5.28	4.93	5.09	**4.92**	4.89
Gl-L	5.36	5.47	4.36	4.67	4.37	5.41	4.27	3.47	4.48	4.92	4.91	**4.70**	4.37
T-L	5.43	5.46	4.11	4.45	4.36	4.87	5.10	3.69	4.70	4.82	5.04	**4.73**	4.65
G-C-Gl	5.68	5.95	4.33	4.97	4.13	4.06	4.30	3.14	4.70	4.77	4.95	**4.63**	4.70
G-C-T	5.83	6.02	4.27	5.14	4.87	4.32	5.24	3.12	4.56	4.98	5.13	**4.86**	4.89
G-C-L	5.96	5.67	4.09	4.29	4.59	5.58	4.19	3.15	4.45	4.78	4.97	**4.70**	4.55
G-Gl-T	5.58	6.06	4.72	4.89	5.09	5.19	4.54	3.39	4.76	4.96	5.01	**4.93**	4.82
G-Gl-L	5.04	5.23	4.04	4.50	4.58	4.90	5.17	3.45	5.17	4.76	4.88	**4.70**	4.48
G-T-L	5.67	5.35	4.63	4.98	4.37	4.43	4.81	3.59	4.79	4.71	4.97	**4.75**	4.67
C-Gl-T	5.64	6.13	4.34	5.34	4.64	5.21	4.49	3.28	4.77	4.95	5.13	**4.90**	4.86
C-Gl-L	5.15	5.80	4.09	4.65	4.35	4.04	4.80	2.90	4.86	4.56	4.94	**4.56**	4.52
C-T-L	5.53	5.86	4.30	4.55	4.68	4.96	4.52	3.25	4.80	4.87	5.12	**4.77**	4.71
Gl-T-L	5.77	5.48	3.94	4.87	4.45	4.71	5.08	3.54	4.77	4.77	5.09	**4.77**	4.64
Mean	**5.48**	**5.70**	**4.29**	**4.75**	**4.49**	**4.75**	**4.648**	**3.29**	**4.95**	**4.77**	**5.01**		

[a] Mid-component average is the yield average of sole cultivars making up mixtures (e.g G-C=(4.7+4.81)/2; G-C-Gl=(4.7+4.81+4.61)/3)

Appendix 4.2 Two-way G x E table for protein (%) of five sole cultivars and twenty two-way and three-way mixtures across twelve environments

Entry	Edmonton Conventional 2016	Edmonton Conventional 2017	Edmonton Organic 1 2016	Edmonton Organic 1 2017	Edmonton Organic 2 2017	Certified Organic 2016	Beaverlodge 2016	Beaverlodge 2017	Lethbridge 2016	Lethbridge 2017	Kernen 2016	Kernen 2017	**Mean**	Mid-component average
Go Early	13.15	16.23	11.42	15.40	14.47	12.41	12.03	13.80	12.97	16.1	11.42	16.0	**13.78**	-
Carberry	12.3	14.97	11.25	14.87	14.43	10.81	12.08	14.57	11.83	16.2	11.27	16.0	**13.38**	-
Glenn	13.34	16.20	12.77	15.37	14.07	11.39	13.23	15.43	12.45	16.5	11.76	16.1	**14.05**	-
CDC Titanium	12.52	16.30	11.60	15.07	14.73	12.07	12.12	15.10	12.27	16.0	11.88	16.7	**13.86**	-
Lillian	14.71	17.07	12.30	16.57	14.70	11.74	13.53	14.87	13.34	16.3	12.56	16.1	**14.48**	-
G-C	12.86	15.63	11.47	15.30	14.47	11.79	12.25	14.13	12.44	16.0	11.93	15.7	**13.66**	13.58
G-Gl	12.97	16.40	11.76	15.60	14.23	11.71	12.80	14.40	12.63	16.1	11.52	15.9	**13.84**	13.92
G-T	12.64	16.23	11.67	15.30	14.13	12.27	12.27	14.60	12.78	16.0	11.59	15.8	**13.77**	13.82
G-L	13.47	16.53	11.66	15.10	14.40	12.16	12.49	14.37	12.91	16.4	11.73	16.1	**13.94**	14.13
C-Gl	12.49	15.77	12.26	16.10	14.90	11.33	12.81	14.90	12.13	16.3	11.68	15.7	**13.86**	13.72
C-T	12.62	15.67	11.44	15.40	14.70	11.29	12.08	14.90	12.50	16.2	11.87	16.1	**13.73**	13.62
C-L	13.14	15.50	11.70	15.60	14.87	11.47	12.95	14.73	12.68	16.1	11.67	15.8	**13.85**	13.93
Gl-T	12.8	16.30	12.10	16.17	14.97	11.36	12.54	15.33	12.50	15.5	11.88	16.4	**13.99**	13.96
Gl-L	12.81	16.30	12.45	16.50	15.27	11.47	12.64	15.27	12.52	16.0	11.69	15.9	**14.07**	14.27
T-L	13.17	16.73	12.18	15.53	14.77	12.15	12.59	14.93	12.88	15.9	11.76	16.8	**14.12**	14.17
G-C-Gl	12.76	15.73	11.86	16.03	14.03	11.54	12.43	14.60	12.43	16.3	11.35	16.2	**13.77**	13.74
G-C-T	12.59	15.97	11.49	15.33	14.93	11.65	12.45	14.40	12.69	15.9	11.49	16.2	**13.76**	13.68
G-C-L	13.16	16.37	11.92	15.40	14.83	11.43	12.15	14.27	12.52	16.3	11.76	15.8	**13.83**	13.88
G-Gl-T	12.58	16.30	12.29	15.80	14.73	12.07	12.39	14.87	12.79	16.9	11.77	16.1	**14.05**	13.90
G-Gl-L	12.88	16.30	11.91	16.17	14.47	11.82	12.75	14.63	12.94	15.8	11.79	15.9	**13.95**	14.11
G-T-L	13.09	16.67	11.91	16.00	13.87	12.04	12.38	14.63	12.11	16.2	11.80	16.2	**13.91**	14.04
C-Gl-T	12.68	16.07	12.12	16.67	14.07	11.72	12.60	15.27	12.22	16.3	11.69	15.9	**13.94**	13.77
C-Gl-L	12.77	16.00	11.52	15.90	14.00	11.50	12.62	14.80	12.66	16.5	11.73	15.7	**13.81**	13.97
C-T-L	12.83	16.07	12.15	15.57	14.67	11.43	12.38	14.80	12.49	16.1	11.96	16.0	**13.87**	13.91
Gl-T-L	12.19	16.37	11.68	16.10	14.60	11.93	12.99	15.27	12.55	16.0	11.66	15.8	**13.93**	14.13
Mean	**12.94**	**16.15**	**11.87**	**15.71**	**14.53**	**11.71**	**12.54**	**14.76**	**12.57**	**16.1**	**11.73**	**16.0**		

[a] Mid-component average is the yield average of sole cultivars making up mixtures (e.g G-C=(13.78+13.38)/2; G-C-Gl=(13.78+13.38+14.05)/3)

Appendix 4.3 Two-way G x E table for SDS sedimentation volume (mL) of five sole cultivars and twenty two-way and three-way mixtures across twelve environments

Entry	Edmonton Conventional 2016	Edmonton Conventional 2017	Edmonton Organic 1 2016	Edmonton Organic 1 2017	Edmonton Organic 2 2017	Certified Organic 2016	Beaverlodge 2016	Beaverlodge 2017	Lethbridge 2016	Lethbridge 2017	Kernen 2016	Kernen 2017	**Mean**	Mid-component average
Go Early	26.80	31.29	21.91	26.00	32.62	26.67	33.01	32.35	25.34	34.20	27.99	34.99	**29.43**	-
Carberry	21.12	27.06	22.44	26.33	27.72	25.21	28.92	33.27	22.17	34.20	25.61	31.03	**27.09**	-
Glenn	26.67	29.84	28.39	27.67	28.25	23.63	31.56	35.39	25.61	33.41	25.61	35.79	**29.32**	-
CDC Titanium	22.31	27.99	20.85	26.00	28.65	24.02	30.89	32.61	22.18	31.42	26.27	33.01	**27.18**	-
Lillian	22.57	27.06	18.87	26.67	27.46	19.93	28.52	29.97	21.51	35.39	24.29	29.05	**25.94**	-
G-C	25.48	29.18	21.91	27.33	29.97	25.21	33.01	34.20	24.42	34.60	26.12	32.22	**28.64**	28.26
G-Gl	26.8	28.91	24.42	26.00	30.23	25.87	32.21	34.46	26.00	34.20	27.72	35.39	**29.35**	29.37
G-T	25.08	30.63	20.99	26.33	28.39	27.33	33.41	32.22	23.89	35.00	26.01	34.60	**28.66**	28.31
G-L	24.95	29.05	22.83	28.00	31.82	24.55	32.48	32.74	24.29	29.05	27.06	32.61	**28.29**	27.69
C-Gl	25.08	27.59	24.42	27.67	30.23	24.16	29.84	34.73	23.63	33.41	26.40	32.61	**28.31**	28.20
C-T	22.57	26.40	21.78	26.67	28.12	24.95	29.44	32.75	23.10	33.01	26.67	31.03	**27.21**	27.14
C-L	22.84	27.73	20.46	27.00	28.78	22.57	27.59	31.56	22.44	32.22	25.61	28.65	**26.45**	26.52
Gl-T	23.10	28.78	24.29	28.33	29.71	23.37	32.48	34.07	23.76	33.41	26.14	33.80	**28.44**	28.25
Gl-L	22.97	28.39	25.08	27.33	31.82	24.29	30.37	33.80	23.76	33.01	26.14	32.22	**28.27**	27.63
T-L	20.99	28.25	20.99	26.67	28.12	23.89	30.76	32.35	22.57	31.82	26.4	30.63	**26.95**	26.56
G-C-Gl	26.14	29.31	22.70	29.00	29.31	25.74	32.22	33.93	24.95	35.00	25.87	33.41	**28.97**	28.61
G-C-T	23.36	27.99	21.38	27.00	30.76	24.82	32.75	32.88	24.29	31.42	26.93	31.82	**27.95**	27.90
G-C-L	23.36	27.46	21.25	28.00	30.77	23.89	30.89	33.14	24.16	35.00	26.00	31.82	**27.98**	27.49
G-Gl-T	24.55	27.86	23.63	27.00	31.16	25.48	31.42	33.80	24.16	32.61	26.67	34.2	**28.55**	28.64
G-Gl-L	26.93	29.57	22.70	29.00	30.24	23.90	31.82	33.14	24.69	34.60	26.67	33.01	**28.86**	28.23
G-T-L	24.55	28.39	21.12	27.00	28.52	24.16	33.01	32.75	22.31	34.20	25.21	33.01	**27.85**	27.52
C-Gl-T	22.31	28.78	24.42	27.33	28.39	24.29	31.95	34.99	23.63	33.41	26.80	31.82	**28.18**	27.86
C-Gl-L	25.08	27.73	21.25	26.33	29.31	23.63	31.29	32.75	24.69	33.41	26.14	32.61	**27.85**	27.45
C-T-L	23.23	26.67	22.97	28.00	29.05	24.29	29.58	32.75	24.69	34.20	25.46	31.82	**27.73**	26.74
Gl-T-L	23.89	29.71	22.44	27.33	28.78	23.37	31.82*	34.07	23.76	33.80	26.00	32.22	**27.76**	27.48
Mean	**24.11**	**28.46**	**22.54**	**27.20**	**29.53**	**24.37**	**31.25**	**33.23**	**23.77**	**34.20**	**26.23**	**34.99**		

[a] Mid-component average is the yield average of sole cultivars making up mixtures (e.g G-C=(29.43+27.09)/2; G-C-Gl=(29.43+27.09+29.32)/3)

Appendix 4.4 Two-way G x E table for falling number (seconds) of five sole cultivars and twenty two-way and three-way mixtures across twelve environments

Entry	Edmonton Conventional 2016	Edmonton Conventional 2017	Edmonton Organic 1 2016	Edmonton Organic 1 2017	Edmonton Organic 2 2017	Certified Organic 2016	Beaverlodge 2016	Beaverlodge 2017	Lethbridge 2016	Lethbridge 2017	Kernen 2016	Kernen 2017	**Mean**	Mid-component average
Go Early	382	422	319	436	366	515	127	410	358	457	425	408	**385**	-
Carberry	358	399	367	403	378	386	177	371	358	408	397	385	**366**	-
Glenn	288	424	318	371	369	438	177	375	227	478	458	376	**358**	-
CDC Titanium	325	442	465	457	437	491	260	409	343	399	472	438	**412**	-
Lillian	396	454	475	467	474	456	191	484	367	484	504	405	**430**	-
G-C	331	399	334	423	377	404	119	388	297	434	383	383	**356**	376
G-Gl	295	435	352	424	376	357	136	342	244	483	405	401	**354**	372
G-T	338	428	387	432	382	502	121	401	372	357	444	450	**385**	398
G-L	313	470	328	444	399	445	109	411	308	531	436	434	**386**	408
C-Gl	287	411	367	372	376	398	199	343	264	483	447	397	**362**	362
C-T	351	414	400	418	378	397	188	398	323	402	436	409	**376**	389
C-L	410	423	388	418	394	391	159	388	376	489	491	424	**396**	398
Gl-T	373	427	462	429	380	430	228	390	262	450	427	422	**390**	385
Gl-L	337	425	353	440	380	397	188	388	284	429	465	448	**378**	394
T-L	453	453	485	456	434	511	214	438	369	394	478	463	**429**	421
G-C-Gl	296	430	302	394	348	338	179	363	276	352	389	404	**339**	370
G-C-T	348	413	312	422	388	412	129	390	343	320	396	409	**357**	388
G-C-L	291	381	350	399	386	420	135	372	298	390	440	401	**355**	394
G-Gl-T	310	431	376	428	419	450	168	388	300	420	441	439	**381**	385
G-Gl-L	367	435	373	421	384	415	167	407	272	356	388	405	**366**	391
G-T-L	305	438	330	464	403	401	127	419	339	419	444	431	**377**	409
C-Gl-T	378	449	425	427	393	422	183	319	283	484	421	410	**383**	378
C-Gl-L	381	410	373	417	409	447	166	385	317	438	466	414	**385**	385
C-T-L	391	436	417	457	412	414	242	397	352	367	432	435	**396**	402
Gl-T-L	374	**435**	427	425	406	471	175	384	306	387	468	428	**391**	400
Mean	**347**	**427**	**379**	**426**	**394**	**428**	**170**	**390**	**313**	**457**	**438**	**408**		

[a] Mid-component average is the yield average of sole cultivars making up mixtures (e.g G-C=(385+366)/2; G-C-Gl=(385+366+358)/3)

Apendix 4.5 Two-way G x E table for height (cm) of five sole cultivars and twenty two-way and three-way mixtures across twelve environments

Entry	Edmonton Conventional 2016	Edmonton Conventional 2017	Edmonton Organic 1 2016	Edmonton Organic 1 2017	Edmonton Organic 2 2017	Certified Organic 2016	Beaverlodge 2016	Beaverlodge 2017	Lethbridge 2016	Lethbridge 2017	Kernen 2016	Kernen 2017	**Mean**
Go Early	112.1	97.60	95.40	93.87	88.47	96.47	105.7	91.33	87.67	83.67	98.67	105.0	**96**
Carberry	91.27	84.80	86.73	79.40	79.53	80.63	86.67	78.00	76.33	72.33	84.33	91.33	**83**
Glenn	101.8	95.60	93.80	91.50	83.13	95.33	93.33	78.67	79.33	75.33	88.67	100.0	**90**
CDC Titanium	104.3	98.27	89.33	88.73	83.27	92.47	99.00	82.00	84.00	80.00	92.00	101.3	**91**
Lillian	104.4	96.07	92.90	90.33	84.93	93.97	87.00	85.67	82.33	78.33	102.67	97.00	**91**
G-C	104.5	92.43	92.17	89.87	83.13	92.10	102.33	81.33	87.67	83.67	96.67	104.7	**93**
G-Gl	108.4	100.7	92.70	92.43	85.57	96.67	99.67	81.67	84.00	80.00	97.00	105.3	**94**
G-T	107.2	95.47	92.00	90.47	85.43	95.53	98.67	87.00	83.67	79.67	97.33	105.0	**93**
G-L	109.6	95.40	97.33	87.72	88.93	96.83	106.0	87.00	94.34	90.33	99.33	102.3	**96**
C-Gl	96.70	91.47	89.93	87.00	83.03	90.17	96.33	78.00	77.67	73.67	88.00	97.67	**87**
C-T	103.7	93.10	87.43	87.43	79.83	88.03	97.67	79.00	79.00	75.00	91.67	99.00	**88**
C-L	102.5	88.37	90.13	83.67	79.13	89.93	92.33	83.00	80.33	76.33	93.00	95.67	**88**
Gl-T	103.5	94.13	88.40	88.57	86.63	93.13	100.0	86.00	84.33	80.33	93.33	102.0	**92**
Gl-L	105.5	95.87	91.17	88.35	85.97	90.70	99.00	84.00	82.67	78.67	90.00	99.33	**91**
T-L	103.8	95.37	90.80	88.43	84.23	92.27	93.33	78.66	85.33	81.33	92.33	100.0	**90**
G-C-Gl	107.5	91.47	95.38	87.85	85.17	97.57	106.3	81.00	85.67	81.67	97.00	103.3	**93**
G-C-T	106.7	95.40	94.60	90.07	84.77	96.60	94.00	85.66	85.33	81.33	92.67	104.0	**93**
G-C-L	104.3	95.50	93.97	87.70	86.93	94.17	103.0	77.33	90.67	86.67	101.33	102.0	**94**
G-Gl-T	107.0	94.57	95.43	90.30	88.20	96.07	98.67	80.33	86.67	82.67	96.67	103.0	**93**
G-Gl-L	105.8	96.53	95.33	90.30	88.47	98.53	99.00	87.33	85.33	81.33	94.67	101.0	**94**
G-T-L	108.4	98.37	91.70	92.27	87.77	95.17	104.7	84.00	84.67	80.67	98.67	105.0	**94**
C-Gl-T	103.1	93.50	91.50	90.73	84.33	89.77	96.33	79.33	80.33	76.33	90.67	100.7	**90**
C-Gl-L	101.3	94.77	90.67	87.83	84.37	92.50	96.33	87.67	79.33	75.33	89.33	98.33	**90**
C-T-L	103.9	93.83	92.87	85.23	83.63	92.20	94.67	83.00	85.00	81.00	94.33	100.0	**91**
Gl-T-L	102.0	95.50	93.80	87.73	85.08	95.80	100.0	80.00	81.67	77.67	96.00	100.3	**91**
Mean	**104.4**	**94.56**	**92.22**	**88.71**	**84.8**	**93.30**	**98**	**82.68**	**83.73**	**79.73**	**94.25**	**101.0**	

Appendix 4.6 Two-way G x E table for maturity (days) of five sole cultivars and twenty two-way and three-way mixtures across twelve environments

Entry	Edmonton Conventional 2016	Edmonton Conventional 2017	Edmonton Organic 1 2016	Edmonton Organic 1 2017	Edmonton Organic 2 2017	Beaverlodge 2016	Beaverlodge 2017	Lethbridge 2016	Lethbridge 2017	Kernen 2016	Kernen 2017	**Mean**
Go Early	96	92	89	85	85	113	99	109	89	90	87	**94**
Carberry	105	98	91	85	88	123	106	109	94	93	93	**99**
Glenn	120	95	95	86	87	122	106	112	94	92	90	**100**
CDC Titanium	99	92	89	83	86	114	100	108	90	90	88	**94**
Lillian	101	94	88	85	84	114	104	110	90	90	88	**95**
G-C	99	96	90	86	86	114	102	109	92	92	88	**96**
G-Gl	99	93	89	86	87	117	103	111	92	91	89	**96**
G-T	98	92	89	83	85	113	100	108	90	90	87	**94**
G-L	97	93	88	83	84	113	101	110	90	91	88	**94**
C-Gl	105	98	93	87	88	122	107	112	96	93	89	**99**
C-T	101	94	89	85	87	116	105	108	92	92	89	**96**
C-L	104	95	91	85	88	121	108	109	92	93	89	**98**
Gl-T	102	94	90	86	86	119	104	112	94	91	88	**97**
Gl-L	102	95	93	85	87	119	107	111	92	91	92	**98**
T-L	99	93	89	83	85	113	102	109	90	90	88	**95**
G-C-Gl	100	96	90	87	86	117	105	110	92	91	89	**97**
G-C-T	97	94	90	85	8	115	103	109	90	91	88	**88**
G-C-L	98	93	90	82	86	118	103	108	89	93	88	**95**
G-Gl-T	100	94	91	85	85	116	103	109	90	92	88	**96**
G-Gl-L	100	93	89	84	84	116	104	110	91	91	88	**95**
G-T-L	97	93	90	84	84	113	100	109	90	90	87	**94**
C-Gl-T	103	97	92	87	85	118	104	109	92	91	89	**97**
C-Gl-L	108	96	90	86	87	118	107	111	93	93	88	**98**
C-T-L	103	94	90	83	85	116	106	110	91	92	88	**96**
Gl-T-L	105	94	89	84	85	118	106	110	91	90	88	**96**
Mean	**102**	**94**	**90**	**85**	**86**	**117**	**104**	**110**	**91**	**91**	**89**	

Appendix 4.7 Least square means of agronomic traits of five sole cultivars and twenty two-way and three-way mixtures in Edmonton Conventional 2016

Entry	Heading (days)	Light interception (%)	The number of tillers	TWT (g)	TKW (g)
Go Early	59	92.69	939	430.5	40.87
Carberry	58	87.64	1133	440.3	36.2
Glenn	59	85.38	824	452.5	37.47
CDC Titanium	58	95.21	1197	442.6	39.13
Lillian	65	78.61	1035	434.3	38.47
G-C	59	86.05	979	435.0	39.53
G-Gl	57	92.44	805	443.2	40.8
G-T	60	90.49	1019	433.4	40.07
G-L	63	87.61	907	430.6	41.27
C-Gl	58	93.16	877	447.1	38.67
C-T	59	94.74	947	441.4	39.4
C-L	63	87.89	883	440.7	37.4
Gl-T	58	91.42	1091	443.6	38.4
Gl-L	58	93.47	1019	443.6	38.6
T-L	59	87.69	1003	436.0	38.47
G-C-Gl	61	90.53	949	444.0	38.4
G-C-T	60	90.41	1040	439.6	40.13
G-C-L	65	77.66	928	439.2	41.47
G-Gl-T	62	87.80	936	438.9	39.87
G-Gl-L	62	81.36	1067	441.6	40.93
G-T-L	59	89.02	928	437.6	40.87
C-Gl-T	60	89.47	928	441.0	39.4
C-Gl-L	59	88.03	837	446.6	38.33
C-T-L	63	83.39	947	443.2	39.47
Gl-T-L	58	95.16	960	444.2	39.4
Mean	**60**	**88.69**	**967**	**440.4**	**39.32**
F value	1.72	1.67	1.54	5.4	4.54
Entry[a]	**ns**	**ns**	*	***	***
SE[b]	2.34	5.19	107	3.14	0.87
LSD	4.71	10.42	15	6.3	1.75

[a] ns: not significant, *: significant at p≤ 0.05, **: significant at p≤0.01, ***: significant at p≤0.001
[b] Standard error of the difference between two means

Appendix 4.8 Least square means of agronomic traits of five sole cultivars and twenty two-way and three-way mixtures in Edmonton Organic 1 2016

Entry	Heading (days)	Weed biomass (g/m^2)	The number of tillers	TWT (g)	TKW (g)
Go Early	57	114.1	616	425.4	41.46
Carberry	56	92.00	675	435.3	40.73
Glenn	57	107.7	779	452.6	38.87
CDC Titanium	56	79.73	669	439.7	42.13
Lillian	59	164.5	587	428.2	37.73
G-C	55	92.00	656	429.1	42.07
G-Gl	57	149.1	667	434.4	40.73
G-T	54	50.40	661	434.8	42.07
G-L	57	156.8	632	426.6	41.40
C-Gl	57	74.40	616	446.5	40.20
C-T	56	76.27	680	440.1	41.73
C-L	59	196.0	587	434.5	39.87
Gl-T	54	80.53	736	444.2	41.40
Gl-L	58	198.4	669	441.0	41.80
T-L	58	110.4	688	439.2	41.47
G-C-Gl	55	174.1	733	438.5	40.27
G-C-T	56	105.1	651	431.4	39.40
G-C-L	61	170.7	576	432.7	41.13
G-Gl-T	56	69.33	781	440.9	41.80
G-Gl-L	56	62.93	717	435.9	39.53
G-T-L	56	106.1	659	437.8	42.93
C-Gl-T	56	98.40	645	442.9	41.47
C-Gl-L	58	125.1	675	444.4	38.67
C-T-L	57	156.3	659	436.9	42.00
Gl-T-L	60	126.4	635	438.1	40.33
Mean	**57**	**117.5**	**666**	**437.2**	**40.85**
F value	2.72	1.65	0.55	8.63	4.41
Entry[a]	**	ns	*ns*	***	***
SE[b]	1.45	46.73	101.37	3.08	0.86
LSD[c]	2.72	93.95	203.83	6.19	1.72

[a] ns: not significant, *: significant at p≤0.05, **: significant at p≤0.01, ***: significant at p≤0.001

[b] Standard error of the difference between two means

[c] Least significant difference

Appendix 4.9 Least square means of agronomic traits of five sole cultivars and twenty two-way and three-way mixtures in Edmonton Conventional 2017

Entry	Heading (days)	LI (%)	The number of tillers	TWT (g)	TKW (g)
Go Early (G)	61	94	1013	449.3	38.87
Carberry (C)	60	95	1141	465.7	37.47
Glenn (Gl)	60	95	987	471.9	37.13
CDC Titanium (T)	60	97	1125	458.8	40.67
Lillian (L)	64	95	917	452.8	38.07
G-C	61	95	869	462.1	38.33
G-Gl	61	95	880	460.3	38.47
G-T	61	96	944	456.3	40.60
G-L	62	93	837	451.3	38.80
C-Gl	60	96.58	1061	467.4	38.73
C-T	60	96	1045	460.8	40.20
C-L	61	95	939	459.7	38.277
Gl-T	60	97	1141	466.2	39.07
Gl-L	61	96	987	464.2	37.87
T-L	61	96	1013	457.5	40.33
G-C-Gl	61	97	907	462.8	37.40
G-C-T	60	96	1077	455.7	39.13
G-C-L	61	96	939	455.7	38.27
G-Gl-T	61	96	1024	459.3	40.33
G-Gl-L	62	95	1083	459.1	38.93
G-T-L	61	96	1131	456.2	39.80
C-Gl-T	60	95	1035	463.1	39.07
C-Gl-L	61	95	1024	466.2	38.40
C-T-L	61	96	1077	459.3	39.47
Gl-T-L	61	95	901	462.3	39.00
Mean	61	95	1004	460.2	38.91
F value	5.82	1.57	0.98	7.06	3.46
Entry[a]	***	**ns**	***ns***	***	***
SE[b]	0.54	1.05	128	2.8	0.76
LSD[c]	1.08	2.1	257.2	5.62	1.52

[a] ns: not significant, *: significant at p≤0.05, **: significant at p≤0.01, *: significant at p≤0.001**
[b] Standard error of the difference between two means
[c] Least significant difference

Appendix 4.10 Least square means of agronomic traits of five sole cultivars and twenty two-way and three-way mixtures in Edmonton Organic 1 2017

Entry	Heading (days)	Weed biomass (g/m^{-2})	The number of tillers	TWT (g)	TKW (g)
Go Early (G)	48	96.8	725	443.5	41.47
Carberry (C)	47	84.0	709	457.9	42.2
Glenn (Gl)	48	54.4	757	464.8	38.87
CDC Titanium (T)	47	86.9	779	450.7	41.73
Lillian (L)	50	91.5	789	452.2	40.67
G-C	48	46.9	880	451.9	40.93
G-Gl	48	105.3	763	452.7	40.40
G-T	48	95.7	773	450.6	42.13
G-L	49	80.5	763	443.6	40.00
C-Gl	48	40.27	843	459.4	40.47
C-T	47	72.0	720	453.4	42.33
C-L	49	94.1	571	454.6	39.80
Gl-T	47	74.1	843	459.2	41.93
Gl-L	49	92.5	656	457.3	39.47
T-L	49	125.9	747	450.6	41.13
G-C-Gl	48	56.3	699	455.8	40.93
G-C-T	48	67.7	827	453.0	41.87
G-C-L	48	83.2	731	449.2	41.07
G-Gl-T	48	64.3	821	454.8	42.27
G-Gl-L	48	62.7	731	449.1	40.27
G-T-L	48	113.6	661	448.5	40.80
C-Gl-T	48	50.4	816	458.1	41.47
C-Gl-L	48	104.8	736	456.4	39.53
C-T-L	47	70.9	805	451.8	41.93
Gl-T-L	47	109.6	697	455.3	41.13
Mean	**48**	**81**	**754**	**453.4**	**40.99**
F value	9.88	0.84	0.99	4.95	3.69
Entry[a]	***	**ns**	**ns**	***	***
SE[b]	0.33	34.64	97.92	3.08	0.71
LSD[c]	0.65	69.65	196.69	6.18	1.43

[a] ns: not significant, *: significant at p≤0.05, **: significant at p≤0.01, *: significant at p≤0.001**
[b] Standard error of the difference between two means
[c] Least significant difference

Appendix 4.11 Least square means of agronomic traits of five sole cultivars and twenty two-way and three-way mixtures in Edmonton Organic 2 2017

Entry	Heading (days)	The number of tillers	TWT (g)	TKW (g)
Go Early (G)	44	907	436.9	41.53
Carberry (C)	45	768	451.2	41.53
Glenn (Gl)	46	773	465.5	37.87
CDC Titanium (T)	44	1040	448.2	42.27
Lillian (L)	51	629	441.0	40.27
G-C	45	731	443.4	41.20
G-Gl	46	779	451.6	40.40
G-T	45	773	440.5	41.00
G-L	47	784	436.7	40.73
C-Gl	46	805	461.9	38.87
C-T	47	763	443.2	40.60
C-L	50	816	445.8	41.00
Gl-T	44	875	457.6	40.20
Gl-L	49	885	457.5	39.47
T-L	49	832	447.0	40.87
G-C-Gl	46	715	438.9	39.67
G-C-T	45	725	445.6	41.33
G-C-L	48	715	445.0	41.53
G-Gl-T	44	789	451.3	40.87
G-Gl-L	46	853	448.4	40.00
G-T-L	46	805	439.4	40.80
C-Gl-T	45	885	453.2	40.27
C-Gl-L	47	640	456.4	40.13
C-T-L	48	880	448.6	41.47
Gl-T-L	48	699	454.2	40.20
Mean	**47**	**795**	**448.4**	**40.57**
F value	6.36	1.19	5.41	4.3
Entry[a]	***	ns	***	***
SE[b]	1.09	116.41	4.684	0.64
LSD[c]	2.20	233.81	9.41	1.29

[a] ns: not significant, *: significant at p≤0.05, **: significant at p≤0.01, ***: significant at p≤0.001
[b] Standard error of the difference between two means
[c] Least significant difference

Appendix 4.12 Pearson 's coefficients of correlation of all variables for five sole cultivars and twenty two-way and three-way mixtures at Edmonton Conventional

	Heading	Maturity	Height	Tillers	TW	TKW	Yield	LI	Lodging rate	Protein	SDS	Falling Number
Heading												
Maturity	-[a]											
Height	-	0.28***										
Tillers	-	-0.19*	-									
TW	-	-0.38***	-0.76***	-								
TKW	-	-0.2**	0.32***	-	-0.22**							
Yield	-	-	-0.26**	-	0.35***	0.27***						
LI	-0.36***	-0.48***	-0.38***	-	0.48***	-	0.19*					
Lodging rate	-0.25**	0.17*	0.68***	-	-0.67***	-	-0.39***	-0.19*				
Protein	0.22**	-0.67***	-0.64***	-	0.77***	-	-	0.47***	-0.49***			
SDS	-	-0.48***	-0.47***	-	0.65***	-	0.25**	0.36***	-0.51***	0.73***		
Falling number	-	-0.45***	-0.5***	-	0.5***	-	-	0.27***	-0.25***	0.66***	0.37***	

[a] Correlation coefficient not significant (p>0.05)

Appendix 4.13 Pearson 's coefficients of correlation of all variables for five sole cultivars and twenty two-way and three-way mixtures at Edmonton Organic

	Heading	Maturity	Height	Tillers	TKW	TW	Yield	Protein	SDS	Falling number	Weed biomass
Heading											
Maturity	0.66***										
Height	0.55***	0.28***									
Tillers	-0.43***	-0.15*	-0.2**								
TKW	-[a]	-	-	-							
TW	-0.57***	-0.31***	-0.41***	0.27***	-						
Yield	-0.39***	-	-	0.32***	0.37***	0.29***					
Protein	-0.75***	-0.52***	-0.36***	0.37***	-	0.67***	0.4***				
SDS	-0.79***	-0.4***	-0.48***	0.43***	-	0.54***	0.29***	0.72***			
Falling number	-0.19**	-0.4***	-	0.14*	-	0.17*	-	0.27***	-		
Weed biomass	0.76***	0.55***	0.4***	-0.35***	-	-0.63***	-0.5***	-0.66***	-0.72***	-0.39***	

[a] Correlation coefficient not significant (p>0.05)

Appendix 4.14 Pearson 's coefficients of correlation of all variables for five sole cultivars and twenty two-way and three-way mixtures at Certified Organic

	Height	Tillers	TW	TKW	Protein	SDS	Falling number	Lodging rate
Height								
Tillers	-[a]							
TW	-0.24*	-						
TKW	-0.34**	-	0.52***					
Protein	0.35**	-	-0.39***	-0.32**				
SDS	-	-	-0.29*	-0.62***	-			
Falling number	-	-	-	-	-	-		
Lodging rate	0.28*	-	-0.3**	-0.43***	0.38***	0.3**	-	

[a] Correlation coefficient not significant (p>0.05)

Appendix 4.15 Pearson 's coefficients of correlation of all variables for five sole cultivars and twenty two-way and three-way mixtures at Beaverlodge (top), Lethbridge (middle), and Kernen (bottom)

	Maturity	Height	Yield	Protein	SDS	Falling number
Maturity						
Height	0.63***					
Yield	0.18*	0.26**				
Protein	-0.76***	-0.75***	-[a]			
SDS	-0.5***	-0.36***	-0.33***	0.48***		
Falling number	-0.82***	-0.72***	-	0.83***	0.35***	

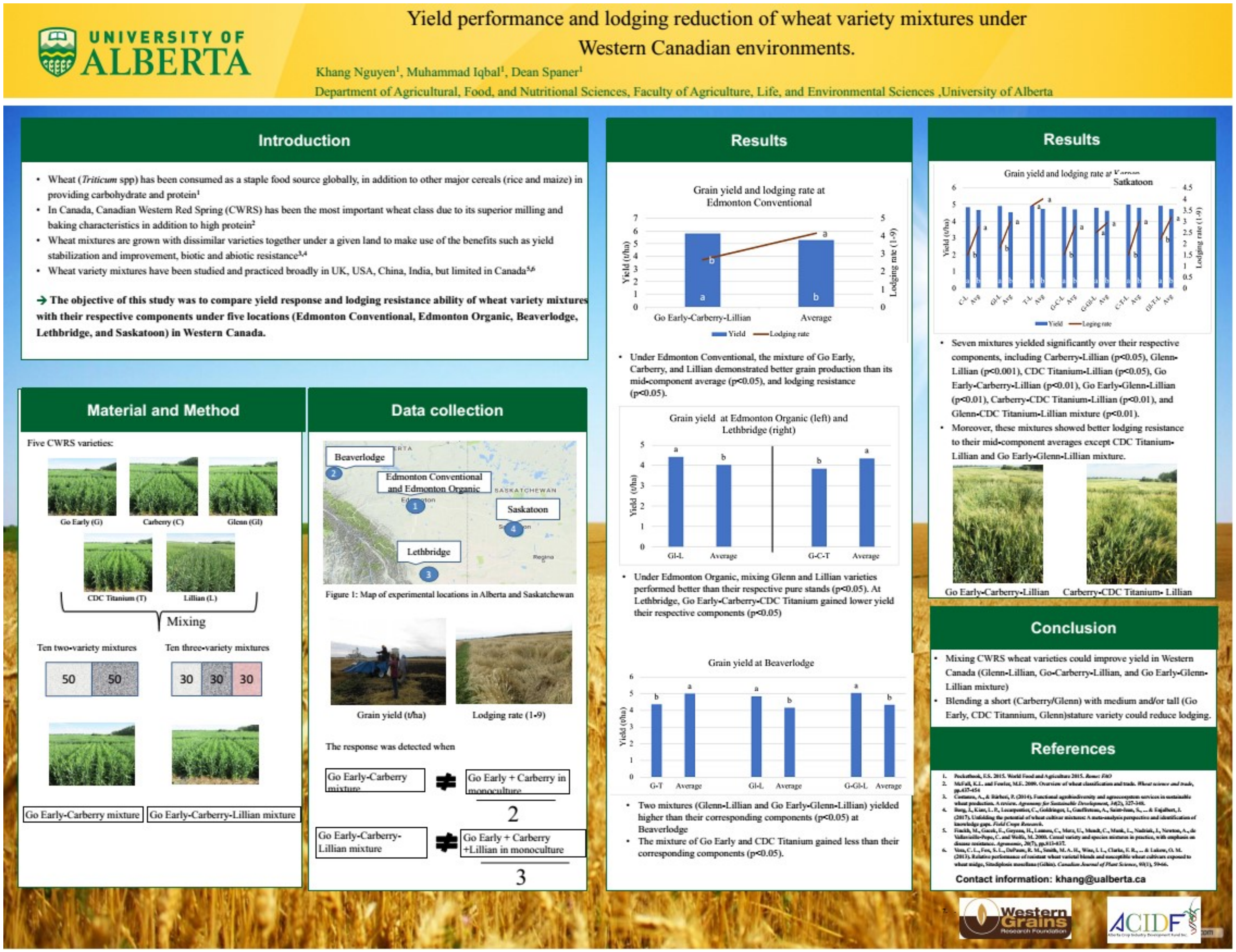
	Maturity	Height	Yield
Maturity			
Height	0.30***		
Yield	-0.73***	-0.28***	

	Maturity	Height	Yield	Lodging rate
Maturity				
Height	-0.59***			
Yield	-0.32***	0.18*		
Lodging rate	-	-	-0.29***	

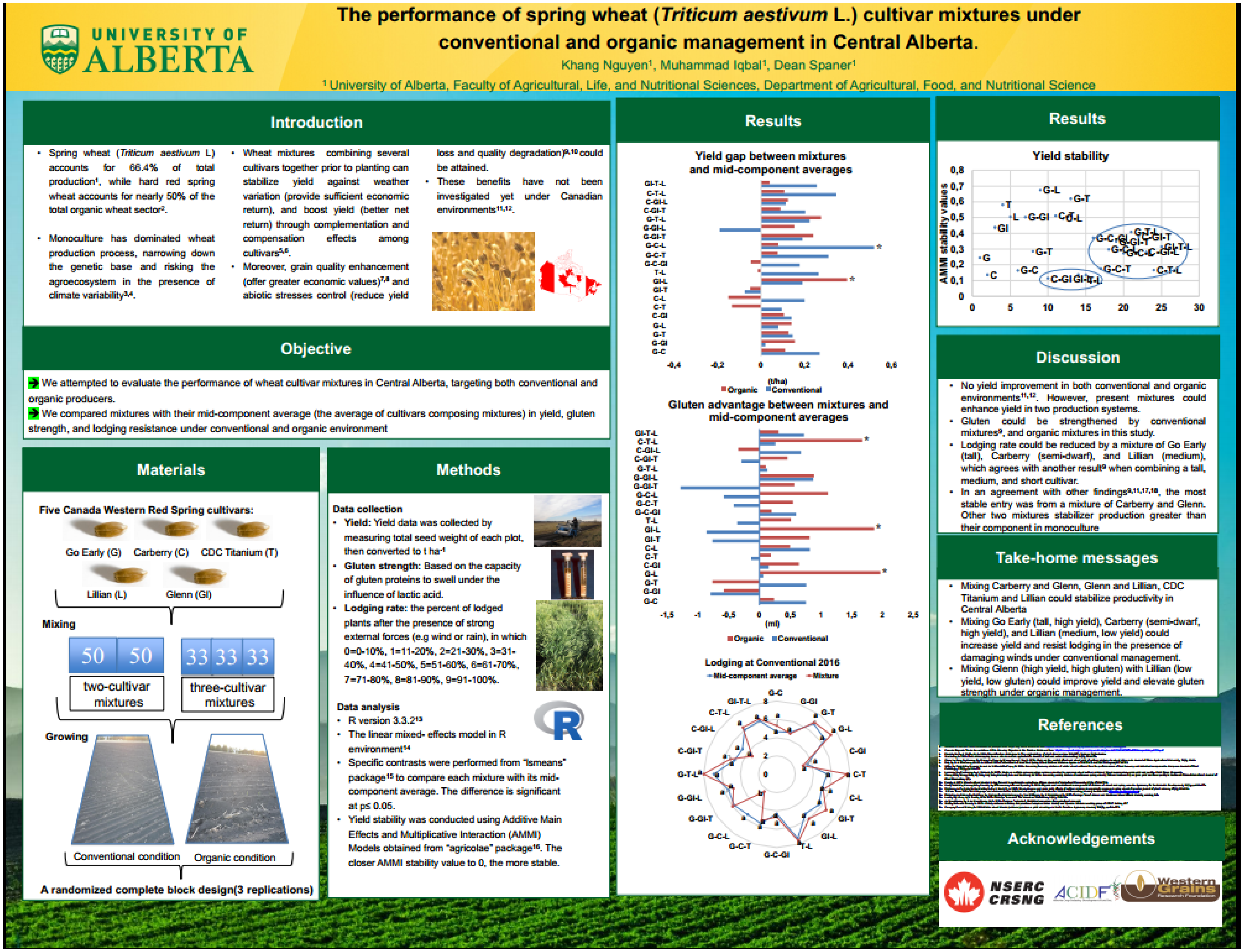
[a] Correlation coefficient not significant (p>0.05)

Appendix 4.16 The mixture Go-Early-Carberry-Lillian against lodging in Edmonton Conventional 2017 (left) and the mixture of Glenn-Lillian in Edmonton Organic 2017 (right)

Appendix 4.17 Poster presented at Cereal Research Symposium 2018 in Red Deer, Alberta, January 10-11, 2018.



Appendix 4.18 Poster presented at Soils and Crops Conference 2018 in Saskatoon, Saskatchewan, March 06-07, 2018.



Appendix 4.19 Poster presented at ALES Graduate Symposium 2018 in University of Alberta, Edmonton, Alberta, March 14 2018