Advanced agronomic practices to maximize feed barley (*Hordeum vulgare* L.) yield, quality, and standability in Alberta environments

by

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Abstract

The grain yields of feed barley (*Hordeum vulgare* L.) have increased at a slower rate than the yields of other major crops in Alberta, and seeded barley acres have declined over the past 20 years. Agronomic management and cultivar specific responses to management may provide solutions to increase grain yields and address production constraints such as lodging and quality limitations. Field experiments were conducted in 2014, 2015, and 2016 at four rainfed and one irrigated site in Alberta to evaluate the effects of seeding rate, post-emergence N, the plant growth regulator chlormequat chloride (CCC), and foliar fungicides on feed barley production. A separate field experiment was conducted to evaluate the effect of an advanced agronomic management package comprised of post-emergence N, CCC, and dual foliar fungicide on 10 feed barley cultivars. The largest yield increases (up to 19%) occurred when post-emergence N was applied in irrigated or high precipitation conditions and when levels of N applied at seeding were relatively low. Foliar fungicides resulted in small (3%) yield increases in the low disease pressures encountered in the study. Some agronomic and yield responses to dual fungicide and CCC depended on seeding rate. Chlormequat chloride did not markedly reduce height and lodging. Genetic lodging resistance was the best tool for lodging reduction in the study. Advanced agronomic management increased grain yield by 9.3% across all cultivars that all responded similarly. The highest yielding and quality cultivars were two-row. Of concern, recently registered cultivars (2008-2013) demonstrated static or negative yield gains compared with cultivars registered up to 13 years prior (2000). The 9.3% yield increase from advanced management was three times

larger than the genetic yield gains observed across 10 cultivars registered between 2000 and 2013.

Dedication

This thesis is dedicated to my parents, Janice and Lester, for their unwavering support and quiet guidance that helped me down the path I walk on today.

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Contributions of Authors

Dr. Sheri Strydhorst was responsible for the experimental design, acquiring funding, and financial management of the research program.

The candidate was responsible for co-conducting all field trials with the assistance of Alberta Agriculture and Forestry technical staff. Field-site technical support, including seeding, treatment application, data collection, and harvest was provided by: Doon Pauly and technical staff (Lethbridge), Dr. Kabal Gill and technical staff (Falher), Robyne Bowness and Trina Dubitz and technical staff (Killam), and the technical staff at Crop Diversification Center North (Bon Accord).

The candidate was responsible compilation of all data, statistical analysis, and writing of the manuscript. The thesis was written by the candidate with the editorial assistance of co-supervisors Dr. Sheri M. Strydhorst and Dr. Linda M. Hall and committee member Dr. Stephen Strelkov. Dr. Rong-Cai Yang provided statistical analysis support throughout.

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List of Abbreviations

ADF	Acid detergent fiber
ADG	Average daily gain
CCC	Chlormequat chloride
DM	Dry matter
FHB	Fusarium head blight
GA	Gibberellic acid
ha	Hectare
hL	Hectoliter
kg	Kilogram
L	Liter
m	Meter
N	Nitrogen
NBPT	*N*-(n-butyl) thiophosphoric triamide
NDF	Neutral detergent fiber
PGR	Plant growth regulator
PLAD	Percent leaf area diseased
SBU	Seedbed utilization
SR	Seeding rate
SRxPGRxFung	Seeding rate x PGR x Fungicide combination
TXP	Trinexepac-ethyl

Chapter One: Introduction

1.1. Background

Barley (*Hordeum vulgare* L.) is the second-most grown small grain cereal crop in Alberta, with the province typically growing 51% of the total annual Canadian barley production (Statistics Canada, 2017). Barley is classified according to spike morphology as either two-row or six-row and marketed according to end-use for food, malting, or livestock feed. Barley is the main feed grain for Alberta's cattle industry of 4.8 million animals (Statistics Canada, 2016a). The majority of seeded barley hectares in Alberta are sown to feed barley cultivars, 0.53 million ha or 64% in 2015 (Agriculture Financial Services Corporation, 2016), but this figure underestimates the land area contributing to feed production because the majority of seeded malt hectares are sold as feed due to infrequent malt quality acceptance (BMBRI, 2012). Barley was grown at least once every 4 years in 52% of 223 surveyed fields in Alberta between 2007 and 2010 (48% of fields did not grow barley), and of the fields that had barley in the 4-years, 58% grew barley 1 in 4 years, 27% grew barley 2 in 4 years, 10% grew barley 3 in 4 years, and 4% grew barley all 4 years (personal communication, Julia Leeson, 2017). Therefore, the majority of fields in Alberta had barley grown less frequently than 1 in 2 years and fungal disease inoculum pressure in longer rotations such as these (2 overwinter periods) is sufficient to reduce fungal disease inoculum pressure (Duczek et al., 1997). Current feed barley agronomic management practices in Alberta consist of nitrogen (N) requirements met at

the time of seeding, weed control at pre-seeding or pre-emergence and in-crop, and foliar fungicide use if environmental conditions and field history are conducive to foliar disease development. Current recommendations from Alberta Agriculture and Forestry indicate the optimal seeding rate for feed barley production is 210 plants m^{-2}. Malt barley cultivars that were intended for malt end-use, but then sold into the feed end-use market because of failure to achieve a malting grade, may have been managed more intensively with a higher optimal seeding rate of up to 300 plants m^{-2} (O'Donovan et al., 2011; 2017) and with a higher likelihood of a foliar fungicide application. Barley also plays an important role in diversifying the western Canadian crop rotation, and increased crop diversity results in reduced disease and insect outbreak risk and ultimately higher yields (Harker et al., 2014; O'Donovan et al., 2014; Turkington et al., 2012). Despite this, barley acres have been declining steadily by an average of 3% per year over the last 20 years in Alberta (Statistics Canada, 2017). Average on-farm barley yield gains from 1991 to 2016 are 31 kg ha^{-1} $year^{-1}$ (1%), and are advancing at a slower pace than the 52 kg ha^{-1} $year^{-1}$ (3%) on-farm yield gains observed for the major cereal crop in Alberta, Canada western red spring wheat (Statistics Canada, 2017). High barley yields are required to balance low commodity pricing of feed barley, but the ten-year average barley yield in the province, 3.57 MT ha^{-1} (Statistics Canada, 2017), is well below the potential yield. This thesis investigates solutions to address barley production constraints related to nitrogen (N) fertility, lodging, and foliar disease. Determining both cultivar response to agronomic management and the effects of improved agronomic management practices (seeding rate, post-emergence N, plant growth regulator (PGR)

application, and foliar fungicides) is necessary to increase grain yields in Alberta and to keep barley an economically competitive crop in the western Canadian rotation.

In addition to higher yield, improved feed barley quality is also desirable. Feed barley grain quality is defined mainly by high test weight, but other factors including high grain starch and low fiber concentration also contribute to improved quality. Canada No. 1 Feed Grade barley specifies a test weight above 59 kg hL^{-1}, (Canada Grain Act, 1970). Surber et al. (2000) concluded that starch concentration was useful in determining cattle feed efficiency and that high starch and low acid detergent fiber (ADF) concentrations increase feed barley quality. Improved feed barley quality is desirable because of improved feed efficiency in feedlot cattle (Grimson et al., 1987; Mathison et al., 1991), higher digestibility (Yang et al., 2013), avoidance of price discounts associated with downgrading, and reduced costs associated with transportation and equipment grain handling capacity (Mathison, 2000). Test weight, grain starch, ADF, and neutral detergent fiber (NDF) varied between barley cultivars and across Manitoba environments (Campbell et al., 1995) but little information is available on the starch, ADF, and NDF concentrations of localized barley cultivars grown in Alberta. Very limited information exists for the quality response of barley to agronomic management, particularly for the management practices of seeding rate, post-emergence N, PGR application, and foliar fungicides. Opportunity exists to improve feed barley quality by examining the quality response to agronomic management, cultivar selection, or a combination of the two factors across the variable edaphic production environments in Alberta.

The effects of seeding rate on barley yield and agronomic responses have been established in western Canadian environments (Jedel and Helm, 1995; Lafond, 1994a; O'Donovan et al., 2011; 2012). However, the effect of seeding rate on feed quality requires investigation. Examining interactions between seeding rate and other agronomic practices for grain yield and agronomic response is required because of the physiological effects of higher barley seeding rates including shortened maturity, crop uniformity, and reduced tiller production (O'Donovan et al., 2011; 2012). These physiological responses to seeding rate may influence barley yield, agronomic, and quality response to other agronomic practices.

Barley N requirements are traditionally met prior to seeding or at seeding by applying mineral N fertilizer in Alberta. Availability of additional N just prior to the beginning of stem elongation (BBCH 30) (Lancashire et al., 1991), the time of maximum crop N uptake in cereals (Baethgen and Alley, 1989), may maximize grain yield. However, elevated volatilization risk for surface applied N fertilizers may warrant the addition of a urease inhibitor such as *N*-(n-butyl) thiophosphoric triamide (NBPT) (Grant and Wu, 2008). Investigation into the agronomic response (lodging and maturity) and grain quality response of additional post-emergence N on spring barley production is also required to determine the agronomic suitability of post-emergence N application.

Chlormequat chloride (CCC) is a gibberellic acid (GA) inhibiting PGR that reduces cereal height and lodging by inhibiting the production of GA during stem elongation (Berry et al., 2004). Although lodging is a production constraint affecting grain yield and quality in Alberta (Jedel and Helm, 1991), information is limited on the effect of CCC on

barley production in western Canada. The effects of CCC on barley height and yield were variable and cultivar-specific in eastern Canada (Clark and Fedak, 1977; Ma and Smith, 1991a), and investigation is required in western Canada and in recently registered and localized barley cultivars.

Foliar fungicides protect photosynthetic leaf area and yield potential by inhibiting fungal spore germination or infection of the leaf. The triazole fungicides (demethylation inhibitors) and strobilurin fungicides (quinone outside inhibitors) comprise the group 3 and 11 foliar fungicides, respectively (FRAC, 2014), and they are the two main fungicide groups available for foliar application in Alberta. Fungicide application must protect the upper canopy leaves for maximum yield protection (Turkington et al., 2015). However, yield responses may differ between single applications at full flag leaf emergence (BBCH 39) and two weeks later after spike emergence because of the different disease protection windows. Dual applications at both BBCH 39 and two weeks later may increase yield compared with single applications because of a prolonged disease protection window.

Examination of feed barley responses to agronomic management practices alone, in combination, and on 10 feed barley cultivars using a systems-based approach could provide information to barley growers and industry to reduce existing feed barley yield gaps, improve agronomic factors, and enhance feed grain quality in Alberta. Additional benefits beyond higher grain yield and quality may occur, such as diversification of crop rotations due to increased barley acres, increased profitability for crop producers, and more efficient use of crop production inputs.

1.2. Hypothesis and Research Objectives

The overall hypothesis of this thesis was:

The agronomic management practices seeding rate, post-emergence N, CCC, and foliar fungicide, either alone or in combination, will result in increased feed barley grain yields and improved agronomic and quality traits, and under high precipitation environmental conditions, these increases will be larger in magnitude than when dry conditions occur. In addition, under high precipitation conditions, responses to advanced agronomic management will be cultivar specific compared to a set of cultivars with differing genetic disease and lodging resistance.

To test this hypothesis, the following research objectives were formed:

1.2.1. Determine the grain yield, agronomic, and quality responses of cv. Amisk feed barley to seeding rate, CCC, and foliar fungicide application combinations in Alberta production environments.

Combinations of seeding rate, CCC, and foliar fungicides may address production constraints such as lodging and foliar disease pressure that limit feed barley grain yields. The effects of seeding rate and foliar fungicides have been studied singly or in combination with other factors (O'Donovan et al., 2012; Turkington et al., 2012), but interactions between seeding rate and foliar fungicide application timing across the variable edaphic environments of Alberta are not well understood. Additionally, the effects of CCC on feed barley height, lodging, grain yield, quality, and other agronomic

factors are unknown in western Canada. Variable effects of CCC on barley height and grain yield were reported in eastern Canada (Clark and Fedak, 1977; Ma and Smith, 1991a; 1992a). Interactions between CCC and seeding rate and foliar fungicides are possible because of the effects of seeding rate and CCC application on plant morphology. Therefore, the response of cv. Amisk feed barley to 16 combinations of seeding rate, CCC, and foliar fungicide was examined in Chapter Three under the following null hypothesis:

- Seeding rate, CCC, and foliar fungicides have no effect on cv. Amisk feed barley yield, agronomic, and quality responses.
- Interactions will be absent between seeding rate, CCC, and foliar fungicide application.
- Environmental conditions will not affect the response of cv. Amisk feed barley to combinations of seeding rate, CCC, and foliar fungicide.

1.2.2. Determine the grain yield, agronomic, and grain quality responses of cv. Amisk feed barley to post-emergence N application in Alberta production environments.

Additional N applied just prior to BBCH 30 may increase barley grain yield. Nitrogen applied at BBCH 30 tended to increase barley grain yield in South American spring malt barley production (Baethgen et al., 1995). Because N applied at seeding has been shown to affect grain yield and agronomic responses in western Canada, the lodging, maturity, and grain quality response to post-emergence N will be examined. The addition of the urease inhibitor NBPT to surface applied post-emergence N

fertilizers may reduce N volatilization losses (Watson et al., 1994) and influence yield, agronomic, and quality responses compared to unamended N treatments. Therefore, barley yield, agronomic, and quality response to NBPT will be quantified. Feed barley response to increasing rates of post-emergence N and NBPT were investigated in Chapter Four with the following null hypothesis:

- Post emergence N at increasing rates does not affect yield, agronomic, and quality responses of cv. Amisk feed barley.
- The urease inhibitor NBPT does not improve the response of cv. Amisk feed barley to post-emergence N application
- Environmental conditions do not influence feed barley response to post-emergence N.

1.2.3. Quantify interactions between post-emergence N and combinations of seeding rate, CCC, and foliar fungicide for cv. Amisk feed barley in Alberta environments.

Identifying interactions between post-emergence N and seeding rate, CCC, and foliar fungicide may provide opportunities to increase grain yields, agronomic performance, and input use efficiency. In Ontario and Finland winter wheat production, foliar fungicide increased grain yield to a greater degree when higher rates of post-emergence N were applied (Brinkman et al., 2014; Olesen et al., 2000; 2003). In western Canada, malt barley lodging severity increased with increasing pre-emergence N rate when a high versus a low seeding rate was used (O'Donovan et al., 2011). Therefore,

interactions between post-emergence N and seeding rate, CCC, and foliar fungicides were investigated in Chapter Three and the following null hypothesis was established:

- Post-emergence N does not affect cv. Amisk feed barley response to combinations of seeding rate, CCC, and foliar fungicide application.

1.2.4. Determine the performance and the response of 10 feed barley cultivars to advanced agronomic management and determine if responses are cultivar-specific.

Barley cultivars vary in genetic disease resistance and in response to plant growth regulators and N (Clark and Fedak, 1977; O'Donovan et al., 2011). Therefore, recently released feed barley cultivars may vary in their response to increasing agronomic management intensity. To investigate the effects of and the interactions between cultivar and agronomic management, the following null hypothesis were established:

- Feed barley cultivars do not differ in yield, agronomic, and quality performance in Alberta.
- Agronomic management does not affect yield, agronomic, and quality responses of 10 feed barley cultivars.
- Feed barley cultivars do not differ in their response to agronomic management.
- The performance of cultivars and the response to management do not differ across environments.

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Chapter Two: Literature Review

2.1. Seeding rate in spring barley production

2.1.1 Target plant stand density

The optimal seeding rate is related to the optimal plant stand density, which in turn is related to the resources available for plant development, the length of the growing season, the crop species, and the growing environment. Many Canadian studies report diminishing yield benefits at seeding rates above 210 seeds m^{-2} (Jedel and Helm, 1995; Lafond, 1994a; O'Donovan et al., 2011; 2012; Spaner et al., 2001) and Alberta Agriculture recommends an average target density of 210 plants m^{-2}, or a range of 153 to 315 plants m^{-2} for optimal feed and malt barley production in the province. The range of seeding densities may reflect the diversity of the cropping environments in Alberta, including the length of the growing season and average precipitation. To select the appropriate seeding rate to achieve the target plant density, seed size (thousand kernel weight), germination, and expected seedling mortality must be considered (Alberta Agriculture and Forestry, 2007).

2.1.2. Effect of increasing barley seeding rate

2.1.2.a. Yield effects

Yield approaches a maximum and plateaus as plant stand density increases. After the plateau and maximum, yield may decrease at increasing seeding rates (Baker and

Briggs, 1983), similar to a parabolic curve. Yield increases from seeding rates above the recommended 210 plants m^{-2} were generally small or not significant in western Canadian environments (Jedel and Helm, 1995; Lafond, 1994a; McKenzie et al., 2005; O'Donovan et al., 2008; 2011; 2012). Yield increases diminish at seeding rates above 210 plants m^{-2} because of compensatory effects between higher plant densities and reduced tiller number $plant^{-1}$ at higher seeding rates (O'Donovan et al., 2011; 2012) and decreased kernels per spike (Dofing and Knight, 1992). O'Donovan et al. (2011) reported higher plants m^{-2} and fewer tillers $plant^{-1}$ at 400 seeds m^{-2} compared to 200 seeds m^{-2} that resulted in no significant yield difference between the two seeding rates. However, environmental conditions have been shown to affect the optimal seeding rate. A two year, central Alberta study, conducted in three locations on four spring barley cultivars, found that in dry conditions, lower seeding rates of 129 plants m^{-2} had lower yields compared to higher seeding rates of 172 to 344 plants m^{-2} (Jedel and Helm, 1995). This occurred because of reduced production of unproductive tillers at higher seeding rates (Dofing and Knight, 1992) in a growing season shortened by drought stress.

High seeding rates may decrease yield in some conditions if increased intra-row competition results in stem etiolation and greater lodging (Jedel and Helm, 1995). A study conducted in 24 western Canadian environments reported seeding rates of 100, 200, 300, 400, and 500 barley seeds m^{-2} had no effect on lodging in cv. Meredith malt barley (O'Donovan et al., 2012). However, under spring drilled N fertilization levels above 60 kg ha^{-1}, 400 seeds m^{-2} seeding rate increased lodging to a greater degree compared to 200 seeds m^{-2} (O'Donovan et al., 2011). When environmental conditions

were conducive to lodging in Alberta production systems, higher seeding rates resulted in increased lodging compared to lower seeding rates, and the effect was cultivar dependent (Jedel and Helm, 1995).

In winter wheat production, yield stability increased with increasing seeding rates of 200 and 400 seeds m^{-2} across 26 western Canadian environments(Beres et al., 2016). Therefore, higher seeding rates may be a production risk management tool.

2.1.2.b. Yield component effects

As higher seeding rates result in increased spikes m^{-2}, compensatory effects for tillers $plant^{-1}$ and kernels $spike^{-1}$ occur. In central Alberta, higher seeding rates increased spikes m^{-2} while decreasing tillers $plant^{-1}$ and kernels $spike^{-1}$, which resulted in neutral effects of barley seeding rate on grain yield (Jedel and Helm, 1995). However, when higher seeding rates (344 seeds m^{-2}) hastened maturity, crops with higher rates avoided early fall frosts and resulted in higher yields than lower seeding rates (Jedel and Helm, 1995). Kernel weight was unaffected by seeding rates between 129 and 344 seeds m^{-2} in central Alberta unless early fall frosts resulted in higher kernel weight for the higher seeding rates with shorter maturity (Jedel and Helm, 1995). Lower seeding rates had decreased spikes and tillers m^{-2} and increased spikes and tillers $plant^{-1}$ (Dofing and Knight, 1992). In situations where crop stage uniformity is of concern, such as for the efficacy of a plant growth regulator application or for Fusarium head blight (FHB) fungicide management, higher stand densities may be desirable to decrease tillering to increase crop stage uniformity.

2.1.2.c. Grain quality effects

Positive effects of higher seeding rates have been reported in malt barley production. In a study conducted over three years and eight locations in western Canada, O'Donovan et al. (2012) reported that cv. AC Metcalfe malt barley kernel uniformity and malt quality parameters (low protein) were maintained or improved at 300 seed m^{-2}, but greater than 300 seed m^{-2} presented a quality risk of low kernel plumpness. Similarly, seeding malt barley at 400 seeds m^{-2} provided malt quality advantages including lower protein and increased kernel uniformity compared to 200 seeds m^{-2}, but there were quality disadvantages including decreased kernel weight and plumpness in western Canada (O'Donovan et al., 2011). Similar malt quality results were reported in southern Alberta for seeding rates between 150 and 350 seeds m^{-2} (McKenzie et al., 2005). Reduced protein is desirable in malt barley production (BMBRI, 2012), but low protein is a neutral feed barley quality trait for ruminants. Research is limited on the effect of seeding rate on feed barley quality parameters; however, Jedel and Helm (1995) reported seeding rates between 129 and 344 seeds m^{-2} did not affect test weight in central Alberta except in environments where early fall frosts resulted in higher test weights for the 344 seeds m^{-2} seeding rate with hastened maturity. Seeding rates up to 300 seeds m^{-2} were beneficial for malt quality characteristics (O'Donovan et al. 2012; 2016), but the effects of higher seeding rate on the feed barley quality characteristics: grain starch and fiber concentration have not been examined in the literature.

2.1.2.d. Maturity effect

Multiple studies report hastened barley maturity at increasing seeding rates (Briggs and Ayten-Fisu, 1979; Dofing and Knight, 1992; Jedel and Helm, 1995; O'Donovan et al., 2008; 2011; 2012). Increasing the barley seeding rate from 200 to 300 or 400 seeds m^{-2} decreased time to maturity by 2 and 3 days, respectively (O'Donovan et al., 2008). Lower seeding rates with increased tillers $plant^{-1}$ are undesirable for production in northern latitude environments because late developing tillers may not mature before fall frost (Dofing and Knight, 1992). Low seeding rates can also result in decreased test weight quality if lengthened maturity coincides with early fall frosts (Jedel and Helm, 1995).

2.1.2.e. Crop competition effect

In situations of high weed pressure, higher seeding rates reduce weed biomass and increase grain yield by increasing crop competitiveness (Barton et al., 1992; Harker et al., 2009; Kirkland, 1993; O'Donovan et al., 2000). Doubling barley seeding rate from 300 to 600 plants m^{-2} under high wild oat pressure in organic production systems increased grain yield and crop competitiveness (Mason et al., 2007). Increasing seeding rate also enhanced the efficacy of certain wild oat herbicides (tralkoxydim) at low herbicide application rates (O'Donovan et al., 2001). In central Alberta, the relationship between barley seeding rate and wild oat density was described by non-linear regression and showed that wild oat biomass and weed seed production decreased while barley grain yield increased when higher barley seeding rates were used in zero

tillage systems (O'Donovan et al., 1999). Similarly, O'Donovan et al.(2008)reported reduced wild oat fecundity as barley seeding rate increased from 200 to 400 seeds m^{-2}. Therefore, in the presence of weed interference, low barley seeding rates could result in yield reductions and increases in weed seed production.

2.1.2.f. Disease severity effect

Stand density can affect disease development in broadleaf crops by influencing canopy microclimate conditions, especially under irrigated conditions (Blad et al., 1978; Burdon and Chilvers, 1982; Grau and Radke, 1984; Krupinsky et al., 2002). However, in central Alberta, barley seeding rates between 129 to 344 seeds m^{-2} did not affect the severity of net blotch (*Pyrenophora teres*) or scald (*Rhyncosporium secalis*) under rainfed conditions (Jedel and Helm, 1995). Conversely, higher seed-row barley plant densities caused by lower seedbed utilization (distinct seed-row) had increased disease severity compared to the lower plant densities attained with larger seedbed utilization (spread seed-row), possibly from accelerated spread of inoculum from diseased to healthy plants in closer proximity (Turkington et al., 2004). These conflicting results suggest plant density may affect disease severity in barley in some instances.

2.2. Post-emergence nitrogen use in spring barley

2.2.1. Barley response to nitrogen at seeding

Pre-plant nitrogen (N) requirements for optimal economic feed barley returns range according to cropping rotation, soil type and organic matter content, and average growing season precipitation (Alberta Agriculture and Forestry, 2004). Continuous cropped soils and soils with lower available N in the spring require more N fertilizer at planting to achieve optimal yields. Yield response to N applied at seeding is influenced by soil moisture, growing season precipitation, available N, and factors that decrease crop yield potential such as late seeding and weed competition (Alberta Agriculture and Forestry, 2004). Positive barley yield responses to N applied at seeding are well understood (McKenzie et al., 2004b; O'Donovan et al., 2014; 2008; 2011; 2015). A study conducted in 21 Western Canadian environments examining malt cultivar response to increasing N rate applied at seeding (0 to 120 kg ha^{-1}) reported increased grain yield, tillers m^{-2}, grain protein, and leaf chlorophyll content with increasing N rate (O'Donovan et al., 2015). Another multi-location Western Canadian study reported a quadratic increase in malt barley yield with increasing pre-plant N rates between 0 and 120kg ha^{-1}, with maximum grain yield occurring at 90 to 120 kg ha^{-1} N when precipitation was between 306 and 403mm. However, when precipitation was higher (421mm) in Brandon, MB, yield increase was linear with increasing N rate, suggesting yield was not maximized at 120kg ha^{-1} N in this environment (O'Donovan et al., 2014). In addition to the positive yield effects of increasing N rate at seeding, there were negative agronomic

responses such as lengthened maturity and increased lodging (McKenzie et al., 2004b; O'Donovan et al., 2008; 2015). The malt barley protein increase with increasing rates of N applied at seeding (0 to 120 kg ha^{-1}) was linear and the yield increase was quadratic, suggesting that protein was maximized higher N rates compared to yield (O'Donovan et al., 2014). In south and central Alberta, McKenzie et al. (2004b) reported increasing N rate, applied at seeding, between 0 and 160 kg ha^{-1} resulted in test weight reductions, an important parameter defining feed quality.

Because of distinct end uses and quality requirements, feed and malt barley fertilization recommendations differ. Malting barley requires low grain protein content (Burger and LaBerge, 1985) (11 to 12.5%) to achieve Canadian malting grade and malt barley N fertilization rates are therefore limited by maximum grain protein limitations (BMBRI, 2012). Feed barley production is not constrained by protein maximums, and high protein levels increase the nutritional value of feed barley for monogastric livestock (Newman and McGuire, 1985). Therefore, feed barley fertilizer N recommendations are higher. For 10 barley cultivars in south and central Alberta, maximum barley grain yield occurred when the ratio of available N (in the soil and applied as fertilizer) to grain yield exceeded 28 kg N MT^{-1} grain (McKenzie et al., 2004).

2.2.2. Barley cultivar specific N response

Interactions between barley cultivar and N rate applied at seeding have been reported for protein, lodging, and kernel weight; however, cultivar by N interactions for grain yield were variable. Two multi-location western Canadian studies examining two-

row malt cultivar yield responses to increasing rates of N applied at seeding (0 to 120 kg ha^{-1}) reported that yield response to N rate did not depend on cultivar (O'Donovan et al., 2011; 2015). Counter to these reports, a 20 location study, conducted over 3 years in central and southern Alberta, reported significant cultivar by N rate interactions for grain yield for ten feed, malt, and hulless spring barley cultivars at N rates of 0 to 160 kg ha^{-1} (McKenzie et al., 2004b). Hulless cultivars had lower yields than the feed and malt cultivars, and the yield differences between cultivars were magnified at higher N rates.

A cultivar by N rate interaction for protein resulted from higher protein in hulless cultivars compared with hulled cultivars (McKenzie et al., 2004b). Lodging response to increasing N rate depended on malt cultivar in a study with ideal conditions for lodging (O'Donovan et al., 2015). Kernel weight response to spring applied N rates between 0 and 120 kg N ha^{-1} also depended on malt cultivar (O'Donovan et al., 2011). Information is limited regarding recently registered feed barley cultivar by N rate interactions at N rates above 120 kg ha^{-1}. Further, cultivar by N rate interactions have not yet been studied for post-emergence N applications.

Differences in cultivar nitrogen use efficiency (NUE) may explain reports of cultivar specific yield responses to N applied at seeding. Nitrogen use efficiency is measured as a plant's ability to uptake N from the soil (N uptake efficiency) and convert the N into grain yield (N utilization efficiency). It is calculated by dividing grain yield by total available N (Moll et al., 1982). Nitrogen use efficiency is related to grain yield because higher NUE is a result of higher grain yield per unit applied N. Significant cultivar by N rate interactions for NUE were reported in field and greenhouse tests

involving 12 feed and malt barley cultivars grown in low N (115 to 119 kg available N ha^{-1}) and high N (196 to 198 kg available N ha^{-1}) conditions (Beatty et al., 2010). In low N field conditions, the NUE of cv. Bentley was below average compared to 10 other cultivars, and in high N conditions the NUE of cv. Seebe was below average, while the NUE of three other cultivars (cv. Vivar, cv. Excel, and cv. Ponoka) was above average in both N conditions (Beatty et al., 2010). In a multi-environment study from 1998 to 2007 on 25 barley genotypes, no significant difference in NUE between 2-row and 6-row cultivars was reported, although the 6-row cultivars tested tended to have higher yield and NUE in low N environments compared to 2-row cultivars (Anbessa et al., 2009). Anbessa et al. (2009) also reported that NUE was improved in newly registered cultivars, suggesting that NUE response should be investigated for new barley cultivars. Because recent studies have indicated barley yield and agronomic responses to N rate applied at seeding were often cultivar specific (Anbessa et al., 2009; Beatty et al., 2010; McKenzie et al., 2004b; O'Donovan et al., 2011; 2015), the response of feed barley cultivars to post-emergence N requires field study in Alberta.

2.2.3. Purpose of post-emergence nitrogen application in cereals

Post-emergence N application increases grain yield (Baethgen et al., 1995; Mossedaq and Smith, 1994; Velasco et al., 2012) and grain protein in cereals (Bly and Woodard, 2003; Bulman and Smith, 1993; Karamanos et al., 2005) depending on application timing. When water was not limiting, post-emergence N application at stem elongation increased wheat grain yield (Alcoz et al., 1993; López-Bellido et al., 2005;

Mossedaq and Smith, 1994). Nitrogen use efficiency and total N uptake increased when the total amount of N was split between pre-plant application and post-emergence application, compared to the same total N amount applied pre-plant (Alcoz et al., 1993; Limon-Ortega et al., 2000). Additionally, split N applications can minimize environmental detriments by reducing N losses resulting from nitrate leaching (Kanwar et al., 1988; Scharf et al., 1993) and denitrification (Burton et al., 2008). Split applications additionally provide management flexibility to buffer the economic risk of applying high N rates at seeding if growing season moisture limitations occur, since moisture levels influence the efficacy of N applications on grain protein and grain yield increase (Gauer et al., 1992; Velasco et al., 2012). However, post-emergence N applications will not consistently increase protein content if pre-plant N applications are insufficient to meet yield goals (Bly and Woodard, 2003), and additionally, grain yield reductions can result (Karamanos et al., 2005).

Post emergence N application is relatively uncommon in Alberta barley production and the majority of barley N fertility research in western Canada has focused on N fertility at seeding time and most often in malting cultivars (McKenzie et al., 2004b; 2005; O'Donovan et al., 2008; 2011; 2015; Weston et al., 1993). The effect of post-emergence N application to increase feed barley grain yield has not been studied in Alberta, despite the benefits of post-emergence N application shown in wheat (*Triticum aestivum* L.) on the northern Great Plains (Bly and Woodard, 2003; Karamanos et al., 2005). A Uruguay study examining malt barley's response to post-emergence N rate and timing in high precipitation conditions (>500mm growing season precipitation) using

broadcast urea applied at seeding, BBCH 22, and BBCH 30 reported BBCH 30 was the most responsive time for post-emergence N application for yield increase, but only if N rate at seeding was adequate for early season growth (Baethgen et al., 1995). Additional research is required to determine feed barley yield response to post-emergence N application at the beginning of stem elongation in Alberta.

2.2.4. Post-emergence nitrogen application timing to target yield increase

Yield is maximized when there is adequate N availability during the time of maximum crop uptake. This occurs immediately after BBCH 30, at the beginning of stem elongation in cereals (Baethgen and Alley, 1989; López-Bellido et al., 2005; Mossedaq and Smith, 1994), or from the beginning of stem elongation to heading (Bauer et al., 1987). If N application is delayed until anthesis, grain protein may increase without a corresponding yield increase (Bly and Woodard, 2003; Rawluk et al., 2000; Woolfolk et al., 2002). Malt barley yield increases occurred more often when N was applied at BBCH 30 than at BBCH 22 or at seeding time in high precipitation conditions in Uruguay (Baethgen et al., 1995), suggesting that additional post-emergence N application at BBCH 30 may increase feed barley yield in some Alberta environments.

2.2.5. Post-emergence nitrogen application form

Under aerobic soil conditions, nitrate (NO_3^-) is the primary form of N taken up by plants, followed by ammonium (NH_4^+) (Nadelhoffer et al., 1984; Xu et al., 2012). Nitrate can be adsorbed by roots, but is subject to leaching and denitrification losses. However, nitrate is equally as effective as ammonium as a source of post-emergence applied N

because of rapid uptake and assimilation by established plants (Fageria and Baligar, 2005). The most common liquid N fertilizer worldwide, urea ammonium nitrate (UAN), is a liquid solution of urea ($CO(NH_2)_2$) and ammonium nitrate (NH_4NO_3) comprised of 28% N in northern latitudes to 32% N in more southern latitudes (International Plant Nutrition Institute, 2016). The nitrate, ammonium, and urea fractions of UAN comprise 25%, 25%, and 50% of total the N, respectively. Surface run-off losses of liquid fertilizer may be less than granular fertilizer (Gascho et al., 1998), which indicates that N sources such as UAN are more favourable for post-emergence N application than dry granular sources such as urea.

Volatilization loss of N occurs when urea is hydrolyzed by the soil microbial urease enzyme into unstable carbamic acid (H_2NCOOH), which then decomposes into ammonium and then to ammonia (NH_3) gas and CO_2 gas which are lost to the atmosphere (Terman, 1979). Urease inhibitors such as *N*-(n-butyl) thiophosphoric triamide (NBPT) marketed under trade names such as Agrotain are compounds that can be added to post-emergence UAN applications to reduce volatilization loss by inhibiting urease activity and delaying urea hydrolysis. Urease inhibitors such as NBPT are effective at reducing volatilization N loss on soils with conditions favouring volatilization such as high pH, low organic matter, and low cation exchange capacity (CEC) (Fenn and Hossner, 1985; Watson et al., 1994). Therefore, the addition of a urease inhibitor to post-emergence N applications could help prevent N loss in conditions favourable to volatilization.

Using a single pre-plant N application, or slow, or controlled release forms of N are agronomic tools designed to release N such that it matches the crop's N uptake needs (Shaviv, 2001). Post emergence N applications must be broadcast to avoid crop disturbance. Broadcast post-emergence N, when supplied as polymer coated urea in the early spring, resulted in reduced winter wheat grain yield and protein concentration compared to broadcast urea, ammonium nitrate, or urea treated with the urease inhibitor NBPT because of delayed N release (McKenzie et al., 2007; McKenzie et al., 2010). This suggests that slow or controlled release N did not adequately match crop N needs compared to N forms that were immediately available.

2.2.6. Post-emergence nitrogen application method

Incorporation or deep banding (subsurface) N application methods may reduce volatilization and run-off loss compared to surface broadcast or surface banding (Fageria and Baligar, 2005). Post-emergence, subsurface N applications made in the spring increased grain yield by up to 33% compared to broadcast N applications in no-till winter wheat systems (Rao and Dao, 1996). Despite the benefits from subsurface post-emergence application, the resulting crop disturbance makes subsurface application impractical. Surface broadcasting urea or surface banding of liquid UAN is practical, and when done in conjunction with a significant rainfall event will reduce N loss caused by volatilization (Black et al., 1987).

2.3. Plant growth regulator (PGR) use in spring barley

2.3.1. Effects of lodging in cereal production

Lodging is the permanent displacement of plants from their upright vertical stature caused by stem breakage, root anchorage failure, or a combination of the two (Berry et al., 2004). Mechanically, lodging is related to the bending moment or leverage force on a stem, and if the leverage force exceeds the stem strength, stem breakage will occur, whereas if the leverage force exceeds the root anchorage system strength, root lodging will occur (Berry et al., 2004). Stem breakage most often occurs in the lower internodes of cereals, but it can also occur in the middle internodes (bracking) or below the head in the peduncle (necking). Barley and oats are more susceptible to bracking than wheat (Berry et al., 2004). Several factors influence leverage force at which lodging occurs and these include environmental conditions such as wind speed, rainfall, and soil water saturation. The wind induced bending moment has been expressed mathematically by Baker (1995) and physiological factors such as stem diameter, plant height, head weight, the presence of awns (which increase the drag coefficient of the barley head), and canopy mass all influence the wind bending moment. Because of these physiological factors, lodging differs between cultivars. In addition, the severity of lodging yield loss depends on the genetic susceptibility of cultivars (Kelbert et al., 2004).

When cereals were intensively managed with high N fertility and irrigation, lodging was increasingly problematic (Berry et al., 2000; Caldwell, 1983; Rajkumara, 2008). Lodging was less likely to occur in dry growing seasons because of reduced plant

height and biomass (Caldwell et al., 1988; Clark and Fedak, 1977). Lodging during the grain filling period, within 20 days of anthesis, resulted in the highest cereal yield losses (Berry et al., 2004; Carter and Hudelson, 1988; Fischer and Stapper, 1987). Grain yield losses between 13 and 40% were reported when artificial lodging was induced during the milk and soft dough stages of the barley grain fill period in Alberta (Briggs, 1990; Jedel and Helm, 1991). Lodging yield loss occurred due to decreased canopy photosynthesis (Berry and Spink, 2012; Setter et al., 1997) and to a lesser degree from grain spike height being too low for mechanical harvest (Pinthus, 1973). Globally, barley yield losses due to lodging events have been estimated to be between 28 and 65% (Berry et al., 2004; Gardiner et al., 2016). In addition, lower kernel weight, fewer kernels per m^2, and delayed grain drying reduce grain quality as a result of lodging (Baethgen et al., 1995; Day and Dickson, 1958; Gardiner et al., 2016). Kernel infection from *Fusarium graminearum* when the grain spike was lodged on the soil surface prior to harvest increased mycotoxin content in the grain (Nakajima et al., 2008). In addition to yield and quality reduction, lodging increased harvest costs by up to 50% (Rademacher, 2009).

2.3.2. Purpose of PGR use in cereal production

Plant growth regulators (PGRs) are synthetic compounds that alter plant growth and development by mimicking, altering the function or translocation, or inhibiting the synthesis of endogenous plant hormones (Kurepin et al., 2013; Rademacher, 2015). PGRs are employed in cereal production to reduce lodging by shortening stems through a reduction in internode elongation, thereby reducing culm breakage (Rademacher,

2015). Lodging reduction as a result of PGR application aids harvest management through decreased time required to combine a standing crop and decreasing straw production through stem shortening (Rademacher, 2000), thereby aiding in residue management in no-till systems. Depending on application time, PGRs can also impact root growth, tillering, and other hormone mediated processes in the plant (Bleecker and Kende, 2000; Rajala and Peltonen-Sainio, 2001; Rajala et al., 2002). The primary purpose of PGR application in cereals in western Canada is to decrease lodging by shortening plant height. A secondary purpose for PGRs, which is employed in regions with longer growing seasons and historical PGR use such as Europe, is for cereal yield increase through increased tiller production or increased kernel survival spike^{-1} (Rajala and Peltonen-Sainio, 2001; Waddington and Cartwright, 1986). In eastern Canada, Ma and Smith(1991a) reported that chlormequat chloride (CCC) did not increase barley spikes m^{-2}, but spikelet primordia survival increased (Ma and Smith, 1991b), resulting in occasional grain yield increases of up to 10% in some cultivars (Ma and Smith, 1992a).

2.3.3. Modes of action of PGRs used for lodging reduction in cereals

Globally, the PGR active ingredients used for stem shortening and lodging reduction in cereals include chlormequat chloride (CCC) ((2-chloroethyl)-trimethylammonium chloride) introduced commercially in the 1960s, ethephon ((2-chloroethyl) phosphonic acid) introduced in the late 1980s, and trinexepac-ethyl (ethyl-(3-oxido-4-cyclopropionyl-5-oxo)) introduced in the mid 1990s (Berry et al., 2004; Rademacher, 2015). Ethephon is an ethylene-releasing compound, while CCC and

trinexepac-ethyl are gibberellic acid (GA) biosynthesis inhibitors. In intensive European production systems, the majority of cereal crops receive a PGR application for anti-lodging, with 76% of the winter barley acres in Great Britain receiving a PGR application (Garthwaite et al., 2006). Until recently, ethephon was registered for use in barley in western Canada, formulated as Ethrel® (Bayer CropScience Canada), but barley is no longer on the registered label (Bayer CropScience Canada, 2016) and beyond the scope of this review. Chlormequat chloride is formulated as Cycocel Extra® (460g ai L^{-1} concentration applied at 0.92 to 1.38 kg ai ha^{-1}, depending on winter wheat variety) (BASF Canada, 1991) for use on winter wheat and ornamental plants in Canada; as Cycocel 750A (582g ai L^{-1} concentration applied at 0.757 kg ai ha^{-1}) for use on wheat in Australia (BASF Australia, 2011); as 5C Cycocel® (645g ai L^{-1} concentration applied at 1.613 kg ai ha^{-1}) on wheat, oats, rye, triticale, and winter barley in the UK (BASF UK, 2011), and as CeCeCe® 750 (750 g ai L^{-1} concentration applied between 1.0 and 1.5 kg ai ha^{-1}) on winter and spring wheat, winter and spring barley, oats, rye, and triticale in Ireland (BASF Ireland Ltd., 2015). Chlormequat chloride is also formulated as Manipulator® (620g L^{-1} ai concentration applied at 1.116kg ai ha^{-1}) (Taminco US Inc., 2015), registered in 2015 for use on spring and winter wheat in western Canada, with possible label expansion to barley in upcoming years. Trinexepac-ethyl is not registered for use in barley in western Canada, but it is registered on spring and winter barley in Europe and the UK at 250 g L^{-1} ai concentration applied at 125g ai ha^{-1} (Syngenta UK, 2015). There are currently no registered CCC products or other PGRs registered for use in barley in western Canada.

2.3.4. Gibberellin biosynthesis inhibitors

Gibberellin (GA) is a plant hormone responsible for, among other functions, regulating shoot elongation in plants (Kurepin et al., 2013; Rademacher, 2000). Gibberellin biosynthesis inhibitors are synthetic compounds applied exogenously to inhibit the production of GA in plants, thereby reducing plant height (Rademacher, 1991). The four classes of known GA biosynthesis inhibitors, in sequential order according to their inhibition points in the GA biosynthesis pathway, are omnium-type compounds, nitrogen-containing heterocyclic compounds, 2-oxoglutaric acid structural mimics, and di-hydro GAs (Rademacher, 2000).

Chlormequat chloride (CCC) (Tolbert, 1960) is an omnium-type compound that inhibits *ent*-kaurene early in the GA biosynthesis pathway, and it is commonly applied to cereal crops for lodging reduction (Rademacher, 2000; Rademacher, 2015). First synthesized in 1910 (Kauffmann and Vorländer, 1910), CCC is now the most widely used PGR on cereal crops globally.

Since PGR active ingredients operate on different metabolic pathways or at different stages in the same metabolic pathway, applying multiple active ingredients in a single application may increase efficacy. In addition, CCC activity is relatively slower to begin and longer acting, whereas TXP activity begins quickly and lasts a shorter duration (Rademacher, 2009). Chlormequat chloride was selected for use alone in the current study because it was the first and only GA inhibiting PGR registered for use in western Canada, for use in spring wheat, formulated as Manipulator (Taminco US Inc., 2015), and Engage Agro supported the concept of this testing.

2.3.5. Barley response to CCC

Chlormequat chloride is used mainly in non-barley cereals to prevent lodging (Rademacher, 2000), although it is registered for use in spring and winter barley in the UK (BASF UK, 2011) and both spring and winter barley in Ireland (BASF Ireland Ltd., 2015). Barley was less responsive than wheat to CCC in terms of height and lodging reduction (Clark and Fedak, 1977; Rademacher, 2009). Studies report variable efficacy of CCC in barley and only temporary height and lodging reductions unless multiple CCC applications were made (Clark and Fedak, 1977; Rajala and Peltonen-Sainio, 2008; Ramburan and Greenfield, 2007).

2.3.5.a. Cultivar specific height response to CCC

Reports of the effect of CCC on barley height are mixed, possibly because of cultivar (Clark and Fedak, 1977) and environmental specificity (Ma and Smith, 1992a; Ma and Smith, 1992b), and because studies have examined different application timings. Chlormequat chloride application in spring wheat is recommended between BBCH 31 and 32 (Taminco US Inc., 2015). In winter barley, CCC formulated as Cycocel 5C is registered for autumn application at the four-tiller stage, or for spring application at BBCH 31, before the first node is detectable (BASF UK, 2011). The effects of CCC on barley height were cultivar-specific both for earlier application timing at BBCH 13 to 15 and for later application timing at BBCH 31 to 32 (Caldwell, 1983; Caldwell et al., 1988; Clark and Fedak, 1977; Ma and Smith, 1992a; Ma and Smith, 1992b).

At the earlier growth stages of BBCH 13 to 15, spring barley height response was cultivar dependent in eastern Canada (Clark and Fedak, 1977). In a 53 cultivar study, less than 10% of cultivars showed a significant height decrease, 23% showed a height increase, and 11% showed no response to CCC, with the magnitude of height decrease and height increase ranging from 13.2% reduction to 11.6% increase (Clark and Fedak, 1977). Application of CCC at BBCH 13 reduced spring barley height 14 days after application compared to the control, but at physiological maturity, no height difference was observed in the two cultivars studied (Rajala and Peltonen-Sainio, 2008). The cv. Puma spring barley was unresponsive to CCC at BBCH 31, but only one cultivar was examined in this South African study (Ramburan and Greenfield, 2007). Multiple applications of CCC at BBCH 13, 15, and 39 reduced the height of the 6-row cv. Parkland and two-row cv. Hannchen by 29% and 21%, respectively, when environmental conditions were favourable for plant growth (Larter, 1967). Therefore, multiple CCC applications appear to result in height reductions at maturity; however, the cost and time constraints of multiple applications in the short Canadian growing season may be prohibitive. Additional testing is required, on multiple cultivars, to determine the ideal growth stage for CCC in western Canada.

In barley, Clark and Fedak (1977) reported that cultivar specific height response was unrelated to initial plant height or the cultivar's days to maturity. They also reported a tendency for two-row cultivars to have height reductions of 0-5%, compared to the variable height response (5-10% decrease, unchanged, or 0-10% height increase)

of six-row cultivars. The variable efficacy of CCC in barley cultivars requires further study to determine cultivar specific responses in western Canada.

2.3.5.b. Lodging response

The limited Canadian literature to date reports that CCC had limited effectiveness at reducing lodging in barley, regardless of application stage. When applied at BBCH 13 to 15 on 53 eastern Canadian barley cultivars, CCC only temporarily delayed lodging (Clark and Fedak, 1977). When CCC was applied at BBCH 31-39 or BBCH 40-49 as individual applications, or as two split applications to cv. Puma barley, CCC did not reduce lodging compared to the untreated control (Ramburan and Greenfield, 2007). More study is required to determine if lodging response to CCC is cultivar specific and if it is an effective lodging reduction tool for western Canadian spring barley cultivars and growing conditions.

Lodging response to CCC may be rate specific. In winter wheat, the Cycocel Extra label indicates that CCC application rate in Canada is dependent on cultivar, with some cultivars registered at rates between 0.920 – 1.15 kg CCC ha^{-1} and others registered at higher rates between 1.15 – 1.38 kg CCC ha^{-1} for efficacy (BASF Canada, 1991).

2.3.5.c. Yield response

The effect of CCC on barley yield was dependent on application timing and cultivar. Application at BBCH 13 or BBCH 30 increased grain yield for cv. Saana barley in Finland (Rajala and Peltonen-Sainio, 2008). In other studies, barley grain yield was

unchanged when CCC was applied at BBCH 13 to 15 (Clark and Fedak, 1977; Larter, 1967). In eastern Canada, CCC application at BBCH 30 increased grain yield by 10% in some barley cultivars by increasing the number of kernels spike^{-1} (Ma and Smith, 1992a). Other studies found application at BBCH 30 or BBCH 39 had no effect on barley grain yield (Larter, 1967; Ramburan and Greenfield, 2007). No yield reductions have been reported from CCC application on barley, but occasional yield reductions in wheat have been reported (Johnston et al., 1979). Therefore, the variable yield responses of barley cultivars to CCC application at the beginning of stem elongation (BBCH 30) warrants addition study in western Canadian conditions and in current cultivars.

2.3.5.d. Yield component response

Early CCC application between BBCH 10 and BBCH 25 reduced main stem dominance and increased barley tillering and tiller survival (Ma and Smith, 1991b; Rademacher, 2009; Waddington and Cartwright, 1986; Woodward and Marshall, 1987; 1988). A Quebec field study found CCC application at GS 13, 30, and 39 increased tiller dominance with CCC application in barley (Ma and Smith, 1991b). Counter to this finding, two different Quebec and Finnish studies found CCC application at the beginning of stem elongation (BBCH 30) had no effect on barley tillering (Ma and Smith, 1991a; Rajala and Peltonen-Sainio, 2008).

The Finnish study reported that tiller spike weight was unchanged with CCC application at GS 13 or GS 30 because the number of tiller spike kernels increased while kernel weight decreased at GS 13 only (unchanged at GS 30) in one of the two barley

cultivars under study (Rajala and Peltonen-Sainio, 2008). Chlormequat chloride application at BBCH 13 resulted in reduced abortion of spikelet primordia that resulted in increased grain yield (Ma and Smith, 1991b). Similarly, the Quebec field study reported CCC application at BBCH 30 increased kernels per main culm spike in one of four barley cultivars (cv. Cadette) causing a 10% yield increase in 2 of 4 years (Ma and Smith, 1992a). In the same study, cv. Cadette displayed higher tiller spike kernel weight and unchanged main spike kernel weight when CCC was applied at BBCH 30.

It appears yield increases from CCC application at BBCH 30 in environments with shorter growing seasons is not from increased tillering, but instead from higher number of grains spike^{-1} or higher tiller kernel weight (Ma and Smith, 1992a; Rajala and Peltonen-Sainio, 2008). However, yield component response to CCC depends on growth stage of application, cultivar, and environmental/climatic conditions. Therefore, barley yield component response to CCC application at BBCH 30 requires study in Alberta growing season conditions and cultivars.

2.4. Foliar Fungicide Use in Barley

2.4.1. Major foliar diseases of barley in Alberta

For disease to occur, a fungal pathogen capable of infecting the host plant and an environment with favourable conditions are required (Francl, 2001). The major foliar diseases of barley in Alberta are scald (*Rhynchosporium secalis*), and the netted (*Pyrenophora teres* f. *teres*) and spotted (*Pyrenophora teres* f. *maculata*) forms of net

blotch (Turkington et al., 2011). Seed borne net blotch was detected in 81 to 89% of barley grain samples collected from 160 commercial barley fields between 1995-1997 across Alberta (Turkington et al., 2002). Spot blotch (*Cochliobolus sativus*) is a more minor foliar disease in Alberta, preferring warm and moist conditions that occur more frequently in Ontario and eastern Canada. Leaf rust (*Puccinia hordei*), stem rust (*Puccinia graminis*) and powdery mildew (*Erysiphe graminis*) are considered sporadic barley diseases in western Canada. However, stripe rust infections of barley can have serious impact on yield, and yield losses of up to 72% in susceptible cultivars were reported in Texas (Marshall and Sutton, 1995).

The predominant foliar diseases of barley in Alberta, scald and both forms of net blotch are polycyclic and overwinter on infected crop stubble (Bailey, 2003), spreading by wind and rain splash to the upper leaves of the canopy during the growing season (Ayesu-Offei and Carter, 1971). With the adoption of reduced tillage in western Canada, foliar diseases have increased (Bailey and Duczek, 1996) due to increased amounts of infected crop residue on the soil surface (Kutcher and Malhi, 2010) and slower crop residue breakdown under cool soil surface conditions (Summerell and Burgess, 1989) compared to conventional tillage. The importance of scald and net blotch has increased with reduced tillage and proper identification is necessary to implement appropriate control strategies.

2.4.1.a. Scald of barley

Scald of barley occurs in most temperate barley-producing regions of the world (Mayfield, 1984). Other host species of scald include the annual cereal crop rye (*Secale cereale)*, and weedy or forage species such as *Agropyron sp., Bromus sp., Hordeum sp., Elymus sp.* and *Lolium sp.* (Owen, 1973). Cool air temperatures between 15-20 ^{o}C favour scald conidia germination, sporulation, and infection. Pathogen growth declines at temperatures above 20 ^{o}C (Owen, 1973). Moist leaves and canopy humidity above 90% also favour disease development (Polley, 1971). Disease transmission is by wind and rain splash from inoculum overwintering on infected stubble to the upper canopy leaves, and to a lesser extent by seed transmission (Owen, 1973). Symptoms manifest initially as small (1.0 to 1.5cm in length) water-soaked greyish-green oval lesions (Bailey, 2003). As disease progresses, the tissue in the center of the oval spots will senesce, resulting in a light tan coloured center with darker margins. In addition to yield losses caused by photosynthetic leaf destruction, scald can spread to the grain head late in the season and cause kernel shrinkage and further yield loss. Scald severity can vary widely between years and fields within a geographic region because disease severity is influenced by preceding crop residue, genetic disease resistance of cultivars, and environmental conditions (Turkington et al., 2012). Turkington et al. (2006) reported that elevated scald severity was 3 to 4 times more likely in commercial barley fields that were planted with barley the year prior, and barley cultivars lacking genetic resistance to scald were 4 to 8 times more likely to have elevated scald severity compared to resistant cultivars. Additionally, penultimate leaves of barley from 338 commercial

barley fields were surveyed in Alberta between 1995 and 1997, and scald severity ranged between 0 and 54 %leaf area diseased (PLAD), with an average severity of 2.1 PLAD over all 3 years (Turkington et al., 2006). In central Alberta in 2013, scald incidence in 19 surveyed fields was 63% and average field severity ranged from 0% to 11% PLAD (Rauhala and Turkington, 2014).

2.4.1.b. Net blotch of barley

Net blotch occurs in two forms, with *Pyrenophora teres* f. *teres* being the causal agent of the netted form, and *Pyrenophora teres* f. *maculata* being the causal agent of the spotted form (Smedegård-Petersen, 1971; Williams et al., 2001). In addition to the main host barley, net blotch infection of other genera such as *Avena, Bromus* and *Triticum* has been reported (Shipton et al., 1973), but because of the resistance levels in these species, they are not considered major hosts or a source of primary inoculum (Liu et al., 2011).

The netted form of net blotch appears as dark brown necrotic lines running along the leaf veins longitudinally, and sometimes horizontally, while the spotted form appears as oval brown spots that do not elongate (Bailey, 2003). The pathogen of each form is morphologically identical and although plant infection symptoms can be used to assist in development, an assay using polymerase chain reaction (PCR) can distinguish the two forms in situations where plant infection symptomology overlaps (Williams et al., 2001). Both net form and spot form net blotch thrive in cool to warm (20^{O}C) and damp conditions (Bailey, 2003), and infection spread during the growing season is

positively correlated to increasing daytime temperature (Van den Berg and Rossnagel, 1991). Because net blotch thrives under moderate air temperatures, it is prevalent across western Canada (Bailey, 2003); however, as with scald, disease severity depends on inoculum from the preceding crop stubble and environmental conditions (Turkington et al., 2012). In 338 Alberta commercial barley fields surveyed between 1995 and 1997, the range of net blotch severity was similar to the range of scald severity, between 0 and 54 % leaf area diseased (PLAD), and the average severity of net blotch, 4.7 PLAD over all 3 years, was approximately 2 times greater than the scald severity (Turkington et al., 2006). In central Alberta in 2013, net form net blotch incidence in 19 surveyed fields was 42% and average field severity ranged from 0 to 12 % leaf area infected (Rauhala and Turkington, 2014).

2.4.2. Impact of foliar diseases on barley yield and yield components

Foliar disease reduces barley grain yield because photosynthetic capacity is reduced by the destruction of photosynthetic leaf area (Turkington et al., 2011). Grain yield loss in barley resulting from foliar disease can be significant in western Canada, and losses between 5 and 14% were reported, depending on environmental conditions (Kutcher et al., 2011; Turkington et al., 2012). There is a negative linear relationship between foliar disease severity on the upper canopy leaves and yield loss in barley (Khan, 1987). In Australia, a 10% increase in disease severity resulted in grain yield losses of 400 kg ha $^{-1}$, and grain yield losses between 23% and 44% resulted in the absence of foliar fungicides (Jayasena et al., 2007). Buchannon and Wallace (1962)

reported average yield losses of 10% caused by scald infection. In addition to grain yield reduction, foliar disease reduced test weight, kernel plumpness, and kernel weight in barley (Khan and Crosbie, 1988; Turkington et al., 2015; 2012). Averaged across 28 western Canadian environments, Turkington et al.(2012) reported small kernel weight, test weight, and kernel plumpness reductions between 1 and 2% in the absence of foliar fungicides, and no difference in grain protein. However, in the same study, when barley was grown on barley stubble and disease severity was higher, larger reductions in test weight, kernel weight, and kernel plumpness resulted (Turkington et al., 2012). Appropriate disease management tools such as foliar fungicides or cultural practices such as genetic resistance and crop rotation are required to preserve barley grain yield and quality in the presence of foliar disease risk.

2.4.3. Cultivar genetic resistance to foliar disease

Barley cultivars differ in their genetic susceptibility to foliar diseases. Overall, resistance to scald is poor in Alberta barley cultivars. The resistance to scald of the current three most widely grown feed barley cultivars, cv. Xena, cv. CDC Austenson, and cv. Champion is rated “susceptible”. In 2014, these cultivars comprised close to half a million insured barley hectares in the province, or 41% of all Alberta’s barley hectares (Agriculture Financial Services Corporation, 2016). Despite the lack of scald resistance, grower familiarity and other agronomic characteristics such as grain yield and lodging resistance are favourable in these varieties, may explain their high acreage. Cultivars such as cv. Sundre and cv. Gadsby have a “resistant” scald rating (Alberta Agriculture

and Forestry, 2016a). Although a variety may have resistance to a particular disease, the remainder of the disease resistance package may have different rating for other pathogens. For example, cv. Sundre has a “resistant” scald rating, but a “susceptible” net-form net blotch rating.

Cultivar resistance to net form and spot form net blotch is more common than scald resistance in Alberta. Resistance to each form of net blotch is often different within the same variety. For example, cv. CDC Austenson is rated as “resistant” and “moderately susceptible” to spot-form and net-form net blotch, respectively (Alberta Agriculture and Forestry, 2016a). In general, the degree of resistance to spot-form net blotch in feed barley cultivars is greater than resistance to the netted form. Resistance in feed cultivars to net-form net blotch ranges from “intermediate” to “susceptible”. The six-row feed cultivar, Vivar, is the exception, with a rating of “resistant” to the netted form (Alberta Agriculture and Forestry, 2016a). Resistance ratings to spot-form net blotch are slightly improved and range from “resistant” to “intermediate” for feed barley cultivars. The exceptions are cv. CDC Dolly and cv. Seebee that have ratings of “moderately susceptible” (Alberta Agriculture and Forestry, 2016a).

Consideration of the disease triangle and potential genetic resistance breakdown is necessary when discussing varietal disease resistance. Infection of a resistant cultivar can occur if environmental conditions are favourable and pathogen pressure is high. Similarly, infection in a moderately resistant cultivar may not occur if environmental conditions are not conducive to disease development.

Reduction in the effectiveness of disease resistance in a cultivar may be due to pathogen mutation and/or sexual and asexual recombination. Selection for genetic resistance breakdown is increased by cultivar adoption (area), and decreased by both crop and cultivar rotation (Finckh et al., 2000; Zhan et al., 2008) and by diversity of disease resistance genes in common cultivars (Zhan et al., 2008). Research on rust resistance in US wheat cultivars demonstrated that resistance remained viable for only 5.5 and 5.3 years for stem and stripe rusts, respectively (Kilpatrick, 1975). In a recent review, (Martens et al., 2015) reported genetic resistance to foliar fungal pathogens in western Canadian production systems could be prolonged using heterogeneity through variety rotation and varietal mixtures. Genetic disease resistance in barley varieties is an important tool to mitigate yield loss caused by foliar disease in favourable environmental conditions, but foliar fungicides are necessary to protect grain yield if disease pressure is high, if the pathogen is able to overcome genetic resistance, or if genetic resistance is insufficient.

2.4.4. Fungicidal control of foliar disease

Western Canadian studies reported that foliar fungicide use in barley increased grain yield in the presence of foliar disease and favourable environmental conditions, and the magnitude of increase depended on factors such as precipitation, crop rotation, and cultivar genetic disease resistance (Kutcher and Kirkham, 1997; Kutcher et al., 1999; 2011; Turkington et al., 2015; 2004; 2012). Because grain yield and quality response of cereals to fungicide depended on cultivar resistance, larger yield increases may be

observed in disease susceptible cultivars compared to disease resistant cultivars. The use of a registered foliar fungicide at the correct application timing is a favourable management strategy for disease control and yield preservation when disease pressure is present and cultivar genetic resistance is lacking.

2.4.4.a. Cultivar specific yield response to foliar disease pressure and fungicides

The magnitude of the grain yield response to a foliar fungicide compared to an unsprayed control may differ between cultivars due to differing genetic resistance to disease. Cultivars with adequate genetic resistance to a given disease may have a smaller grain yield increase in response to fungicide application compared to cultivars with poor genetic resistance. For example, foliar fungicide application of propiconazole, prothioconazole, or chlorothalonil resulted in increased grain yield for the susceptible cv. Harrington barley, which had high foliar disease ratings and poor genetic foliar disease resistance, but not for the other cultivars which had lower disease severity ratings and better disease resistance packages (cv. Robust, cv. Excel, cv. Oxbow, TR133, B-1602, AC Metcalfe, and cv. Newdale) (Kutcher and Kirkham, 1997; Kutcher et al., 2012).

2.4.4.b. Fungicide application timing to preserve grain yield

Fungicide efficacy and protection is finite, and a single foliar application does not provide season-long disease control. The flag and penultimate leaves are responsible for the majority of photosynthetic accumulation of carbohydrates during the grain fill stage

in barley (Chen et al., 2008; Jenkyn and Anilkumar, 1990). However, the barley head also contributes to photosynthetic accumulation (Thorne, 1965). Therefore, foliar fungicide application should protect the penultimate and the flag leaf, which emerges fully at BBCH 39, and a second later application may be warranted to further protect the flag leaf if foliar disease pressure is high late in the season, or to protect the grain quality and yield if Fusarium head blight (FHB) infection, caused by *Fusarium graminearum,* is of concern (Jones, 2000). Although pre-flag leaf emergence application timing during early stem elongation (BBCH 32) can increase silage yield (Orr and Turkington, 2000), fungicide application earlier at the 2 leaf stage (BBCH 12) is ineffective at controlling disease throughout the growing season or protecting grain yield and quality (Turkington et al., 2004). Split half rate fungicide applications between herbicide timing at BBCH 12 or BBCH 15 and flag leaf timing at BBCH 39 resulted in lower grain yield and quality and higher leaf disease compared with a full rate fungicide at flag leaf timing in western Canadian barley production (Turkington et al., 2015). Other western Canadian barley research supports later fungicide applications coinciding with flag leaf or head emergence as being more effective at reducing foliar disease severity and increasing yield compared to earlier applications (Kutcher et al., 1999; Orr et al., 1999; Turkington et al., 2004; Turkington et al., 2012), especially in situations of high disease pressure when barley was planted on barley stubble (Turkington et al., 2012).

2.4.5. Mode of action of Group 3 and 11 fungicides

Fungicides are classified by the Fungicide Resistance Action Committee (FRAC) according to their mode of action used to inhibit biological functioning of the fungal pathogen (FRAC, 2014). The triazole fungicides belonging to FRAC group 3 were introduced in the 1970s (Brent and Hollomon, 1995), while the strobilurins belonging to FRAC Group 11 are newer, discovered in 1996 (Bartlett et al., 2002). The triazoles inhibit fungal growth by preventing sterol biosynthesis in cell membranes by targeting the C14-demethylase enzyme in sterol biosynthesis, while the strobilurins prevent fungal growth by inhibiting respiration by targeting ubiquinol oxidase at the quinone outside site (FRAC, 2014). The FRAC Group 3 triazole (demethylation inhibitors) and the Group 11 strobilurin (quinone outside inhibitors) fungicides are active ingredients registered in formulated products to control the predominant barley foliar diseases in Alberta. A single Group 7 succinate dehydrogenase inhibitor active ingredient is available, only with activity on stem rust (*Puccinia graminis f. sp. tritici*) (Alberta Agriculture and Forestry, 2014). Metconazole, propiconazole, prothioconazole, and tebuconazole comprise the triazole active ingredients, while pyraclostrobin, picoxystrobin, and azoxystrobin comprise the strobilurin active ingredients (Alberta Agriculture and Forestry, 2014).

2.5. Interactions between agronomic practices

2.5.1. Examining relationships between agronomic practices within agronomic systems

An agronomic system is composed of multiple agronomic practices applied to the crop in a growing environment. An individual practice that impacts plant growth may have implications on the agronomic system as a whole, and therefore agronomic practices may cause differential agronomic responses when applied in concert compared to independent application. In addition, altering one agronomic component of the crop system may affect the crop agronomic response to other components of the system. Relationships between multiple agronomic practices across diverse growing environments should be understood for optimal management.

2.5.2. Relationship between N and other factors

Post-emergence N is applied at the beginning of stem elongation to increase grain yield. Research on barley responses to post-emergence N application is limited in western Canada, but results from studies examining spring applied N may be used to infer trends regarding the relationship between increasing N rate and other agronomic factors.

2.5.2.a. Nitrogen x PGR

Increasing rates of spring applied N result in increased lodging in cereals (Berry et al., 2000; Caldwell, 1983; O'Donovan et al., 2011; Rajkumara, 2008). The effect of PGR

application on lodging, height reduction, and other agronomic responses in barley may differ at increasing N rates due to increased lodging pressure and plant height as N rate increases. It is important to examine the relationship between post-emergence N rate and CCC to determine if agronomic responses to CCC remain constant at increasing rates of post-emergence N. Ethephon prevented increased lodging at N rates of 120, 150, 180kg ha^{-1} split between seeding and post-emergence in Puma barley (Ramburan and Greenfield, 2007). The effect of CCC and post-emergence N application on barley has not been studied and therefore further investigation is warranted.

2.5.2.b. Nitrogen x seeding rate

Post-emergence N has been reported to increase cereal yields, but its effect at different seeding rates (higher plant populations) is unknown. Additionally, PGR efficacy may be influenced by N rate and seeding rate. In a greenhouse experiment on wheat, stem strength decreased when the highest plant density and N fertilization regime were used in combination than either of the two factors alone (van den Berg and Labuschagne, 2012). Similarly, reports from research on barley in western Canada found lodging at high spring N fertilizer rates was more severe when higher seeding rates were used (O'Donovan et al., 2011). No significant barley yield interaction was reported between seeding rate and relatively low levels of spring applied N (22 to 76 kg ha^{-1} N) in a western Canadian field study that did not measure lodging (Lafond, 1994a). Further investigation is needed to determine the relationship between seeding rate and post-

emergence N application for barley grain yield, lodging, and other agronomic factors such as test weight under field conditions.

2.5.2.c. Nitrogen x fungicide

Examining the relationship between N rate and foliar disease in barley is important to optimize response to N fertilizer rates and fungicide use. The relationship between N rate and disease severity may be linked to the biotrophic or necrotrophic nature of the pathogen present. The major foliar diseases found in Alberta barley production are necrotrophic, while powdery mildew (*Blumeria graminis*) and rusts (*Puccinia spp.*), which are minor or infrequent diseases of barley in western Canada, are biotrophic. Plant diseases caused by biotrophic pathogens increase in severity with increasing N rates because biotrophic fungi benefit from increased N supply in the infected living plant cells (Bainbridge, 1974; Johnston et al., 1979; Tompkins et al., 1992). For example, in Denmark winter wheat systems under powdery mildew pressure, disease severity increased with increasing rates of N (Olesen et al., 2003). Necrotrophic pathogens such as *Septoria nodorum* of wheat decreased with increasing spring applied N rates (Johnston et al., 1979) because more vigorous plants may be better able to ward off disease. Therefore, it may be more likely for an N rate x fungicide interaction to occur in areas in Europe and eastern Canada where powdery mildew is a common barley disease compared to western Canada where necrotrophic foliar pathogens predominate. However, increasing rate of N applied at seeding (0-200 kg ha^{-1}) resulted in increased above-ground dry matter production in a 32 site-year south and central

Alberta study(McKenzie et al., 2004a), suggesting that higher rates of N increased canopy biomass, which may result in a microclimate more conducive to disease development.

In western Canadian spring barley production systems, no interaction between fungicide and pre-emergence N rates (50% or 100% of the soil test recommended rates) was found (Turkington et al., 2012). Pre-emergence N rates above 80 kg ha^{-1}, increasing rates of N were ineffective at increasing spring wheat yield without fungicide application (Johnston et al., 1979). Johnston et al. (1979) attributed this to fungicide application maintaining healthier plants that were better able to utilize the higher N rates compared to diseased plants. Foliar fungicide increased yield compared to the untreated control in winter wheat by 6% to 17% with multiple fall N applications and higher total N rate (75 kg ha^{-1} fall applied + 50 kg ha^{-1} late fall applied) but at conventional fall applied N rates (75 kg ha^{-1} fall applied) yield increased by only 2% to 8% (Kelley, 1993). The interaction between post-emergence N and fungicide has not previously been studied in spring barley under western Canadian environmental conditions, and therefore further investigation is needed.

2.5.3. Interactions between seeding rate and other factors

Higher plant stand densities may be implemented in spring cereal systems to enhance crop uniformity by discouraging tillering (Dofing and Knight, 1992). Crop uniformity is desirable to ensure correct crop staging for products with short application windows such as PGRs and fungicides that target FHB (Bayer CropScience Canada,

2016). Higher plant densities shorten time to maturity, which is desirable for the short growing season found in western Canada (Dofing and Knight, 1992; Jedel and Helm, 1995; O'Donovan et al., 2008; 2011; 2012). The effect of seeding rate on the barley production system may alter the responses of other agronomic practices used in concert on the system.

2.5.3.a. Seeding rate x fungicide

A potential consequence of higher density plant stands is the enhancement of canopy conditions favourable to disease, especially in broadleaf crops (Blad et al., 1978; Burdon and Chilvers, 1982; Grau and Radke, 1984; Krupinsky et al., 2002). Therefore, due to differing disease pressures, the effect of fungicide on grain yield, crop greenness, and protein may be different at higher seeding rates than at lower seeding rates. In 5 central Alberta environments, varying barley seeding rate from 129 to 344 seeds m^{-2} did not influence the severity of net blotch (*Pyrenophora teres*) or scald (*Rhyncosporium secalis*) under rainfed conditions (Jedel and Helm, 1995). However, across six Alberta and Saskatchewan environments, Turkington et al.(2004) reported higher plant densities within the seed row caused by decreased seedbed utilization (SBU) resulted in higher net blotch severity compared to lower densities caused by greater SBU. However, fungicide disease control did not differ between high and low plant densities in the same study (Turkington et al., 2004). Further research is needed to investigate the impact of seeding rate on fungicide efficacy under Alberta rainfed and irrigated conditions. In addition, optimal fungicide application timing may differ between target

seeding rates due to crop canopy dynamics. Increased crop stage uniformity resulting from higher seeding rates may increase the efficacy of fungicide applications requiring precise crop staging, such as for the suppression of FHB.

2.5.3.b. Seeding rate x PGR

Increased lodging due to etiolation and weakened stems caused by increased intra-row competition is a consequence of higher seeding rates (Jedel and Helm, 1995). Barley lodging and height responses to CCC application were not affected by seeding rates ranging from 200 to 500 viable seeds m^{-2} in Finnish spring barley production (Rajala and Peltonen-Sainio, 2008). This indicated that CCC efficacy was not increased at higher seeding rates. However, in eastern Canada, Ma and Smith (1991a) reported CCC application affected the kernel weight of tiller, but not main culm spikes, which indicated that CCC response may be affected by the extent of tillers present. The relationship between seeding rate and CCC on grain test weight is unknown. Because seeding rate influences plant and tiller density, seeding rate may influence agronomic responses to CCC.

2.5.4. Fungicide x PGR interactions

Limited research is available on fungicide x PGR interactions in barley. Recent work examining PGR x fungicide responses in wheat indicates fungicides eliminated the protein reduction resulting from CCC and TXP application when fungicides and PGRs

were applied in concert (Strydhorst et al., unpublished data). The effect of fungicide and CCC application on spring barley yield has not been studied in western Canada.

2.6. Feed barley quality response to cultivar and agronomic management

Test weight is the main parameter determining feed barley quality, and the Canada Grains Act (1970) specifies Canada No.1 Grade Feed Barely test weight must be above 59 kg hL^{-1} to avoid downgrading and price discounts. Feedlot steers fed low test weight barley required up to 6% more dry matter intake for equivalent gain as steers fed high test weight barley (Grimson et al., 1987; Mathison et al., 1991), and digestion of dry matter was less complete with low test weight barley (Yang et al., 2013). Barley with low test weight can also result in increased costs associated with additional processing requirements and reduced equipment handling capacity (Mathison, 2000). Starch, the highly digestible portion of the grain, was positively correlated to test weight, whereas acid detergent fiber (ADF) and neutral detergent fiber (NDF), the less digestible portions of the grain, were negatively correlated with test weight (Campbell et al., 1995). Barley cultivars with relatively high starch and low NDF concentrations tended to be more digestible, have greater energy content, and resulted in better feed efficiency, although NDF digestibility also influenced feed efficiency (Ovenell-Roy et al., 1998b). Furthermore, test weight, starch, ADF, and NDF concentration varied across cultivars and environments in Manitoba (Campbell et al., 1995) and the eastern United States (Ovenell-Roy et al., 1998b).

The effect of agronomic management on starch and grain fiber is unknown in western Canada, but in Sweden, a 90 kg ha^{-1} increase of N applied at seeding resulted in a 4% decrease in barley grain starch concentration accompanied by increased yield and kernel number (Oscarsson et al., 1998). McKenzie et al. (2004b) reported barley test weight decreased by 2% when N rates applied at seeding ranged from 0 to 160 kg ha^{-1} in southern Alberta.

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Chapter Three: Response of cv. Amisk feed barley to seeding rate, chlormequat chloride, and foliar fungicide combinations at increasing rates of post-emergence N in Alberta

3.1. Introduction

Barley is the second-most grown cereal crop in Alberta, accounting for 20% (1.53 million ha) of the seeded acres in the province from 2006 to 2016 (Statistics Canada, 2016b). Feed barley is the primary grain feedstock for the Alberta cattle industry of 4.8 million live beef cattle (Statistics Canada, 2016a). In addition, barley is an important contributor to crop diversity in the western Canadian crop rotation, where 46% of 223 surveyed fields in Alberta grew canola 1 in 2 years between 2007 and 2010 (personal communication, Julia Leeson, 2017). Barley in rotation is beneficial to the system as a whole because crop diversity results in increased yield and reduced insect and disease risk (Harker et al., 2014; O'Donovan et al., 2014; Turkington et al., 2012). For feed barley to be an economically competitive crop choice, high barley yields are required to balance low commodity prices. In comparison with hard red spring wheat, provincial barley yields have been increasing at a slower pace over the past 15 years (Figure 3.1) (Statistics Canada, 2017). Additionally, the yield performance of currently grown feed barley cultivars, registered from 1997 to 2013, has been static, in contrast with currently grown malt cultivar yields that have been increasing with advancing year of registration during the same time period in on-farm rainfed production (Agriculture Financial Services Corporation, 2016) and in provincial Regional Variety small-plot trials (Alberta

Agriculture and Forestry, 2016a) (Figure 3.2). Although on-farm data contains biases such as differential management and cultivar acreage, the provincial Regional Variety small-plot trials compared cultivars under a standard set of management practices and these data show similar trends. Aside from herbicidal weed control, current agronomic management in Alberta feed barley production mainly consists of: all N requirements met at the time of seeding and foliar fungicide use if environmental and field history conditions warrant application. Improved agronomic management may provide solutions to increase yields and maintain feed barley as a competitive crop in the western Canadian rotation. Research was conducted to determine the effect of agronomic practices including: seeding rate, post-emergence nitrogen (N), a plant growth regulator (PGR), and foliar fungicide application, and interactions between these agronomic practices on the yield, quality, and agronomic response of feed barley.

High quality feed barley grain is beneficial because of the resulting feed efficiency. The quality parameters for feed end-use differ from those for malt end-use. Unlike malt, feed barley quality is not restricted by grain protein content. Secondly, the Canada Grains Act (1970) specifies feed barley with test weight below 59 kg hL^{-1} is subject to downgrading and price discounts. Barley digestibility in feedlot cattle increases with increasing test weight (Yang et al., 2013), and each unit (kg hL^{-1}) increase in test weight results in 1.2% less barley required for equivalent weight gain (Grimson et al., 1987). In addition to downgrading, price discounts, and reduced feed efficiency, low test weight barley requires increased grain handling capacity because of the higher grain volumes required for equivalent cattle performance (Mathison, 2000). High test weight

barley also has higher starch and lower fiber concentration compared to low test weight barley (Yang et al., 2013). Starch is the highly digestible component of the barley grain, and starch concentration is positively correlated to energy content and weight gain in feedlot cattle (Surber et al., 2000). Acid detergent fiber (ADF) and neutral detergent fiber (NDF) are negative quality components of feed barley, with NDF being the cell wall components: lignin, cellulose, and hemicellulose. Acid detergent fiber is a sub-component of NDF, comprised of the least digestible cell wall components cellulose and lignin. High ADF barley is less digestible (Engstrom et al., 1992) and barley that was high in NDF and low in starch usually resulted in reduced energy content, digestibility, and feed efficiency (Ovenell-Roy et al., 1998b). Increased feed barley quality is desirable, but the response of feed barley quality to agronomic management has been the topic of limited research.

High precipitation and high N fertility favour grain yields, but also favour lodging, which is a major constraint in feed barley production. Lodging reduces photosynthate production and transport to the filling grain spike (Berry and Spink, 2012), and when lodging occurs during the grain-filling stage, barley grain yield was reduced between 13 and 40% in Alberta (Briggs, 1990; Jedel and Helm, 1991). Other negative impacts of lodging include: reduced harvest efficiency and increased harvest costs (Rademacher, 2009); increased risk of infection by fungal pathogens (Berry et al., 2004); and reduced test weight (Baethgen et al., 1995). A PGR may allow use of higher N rates to increase yields without the consequences of lodging, by reducing stem length. Chlormequat chloride (CCC) is a gibberellic acid inhibiting PGR that was recently registered for use in

wheat in western Canada to reduce lodging by shortening stem length and reducing plant height (Taminco US Inc., 2015). Barley response to CCC in other jurisdictions has been variable. Height decreases between 0 and 13cm, when CCC was applied at BBCH 30, that were occasionally accompanied by lodging reduction, were observed by Ma and Smith (1992a) in Quebec, whereas there was no barley height response to CCC applied at stem elongation in a South African study (Ramburan and Greenfield, 2007).

Although N rates at the time of seeding and their interactions with other factors have been studied, post-emergent N applications are not well understood. O'Donovan et al. (2011) reported more barley lodging at 400 seeds m^{-2} compared to 200 seeds m^{-2} seeding rate with increasing N rate at seeding. In winter wheat (*Triticum aestivum*), Olesen et al. (2000; 2003) reported increased foliar disease severity and increased yield response to fungicide with increasing N rate at seeding. Cereal yield was maximized when N was available at the time of greatest crop uptake, the beginning of stem elongation at BBCH 30 (Baethgen and Alley, 1989; López-Bellido et al., 2005). As such, opportunity may exist to increase barley yields by applying N post-emergence. In high precipitation conditions in Uruguay, malt barley yield was increased more often with post-emergence N applied at BBCH 30 (Lancashire et al., 1991) compared to N applied at seeding or at BBCH 22 (Baethgen et al., 1995).

In contrast to CCC and post-emergence N, the effects of seeding rate on barley production have been studied in western Canada (Jedel and Helm, 1995; Lafond, 1994a; O'Donovan et al., 2011; 2012). Provincial seeding rate recommendations cite a target plant stand density of 210 plants m^{-2}, with a range of 153 to 315 plants m^{-2} (Alberta

Agriculture and Forestry, 2007). Reduced days to maturity and tillering resulting from higher barley seeding rates (O'Donovan et al., 2011; 2012) may increase crop uniformity and may be beneficial for agronomic practices requiring precise crop staging such as CCC application and fungicide application to control Fusarium head blight (*Fusarium graminearum* Schwabe).

Foliar fungicides are employed to protect photosynthetic leaf area from fungal infection, thereby protecting grain yield (Poole and Arnaudin, 2014). Foliar fungicides should be applied after the time of flag leaf emergence for maximum efficacy and yield response (Turkington et al., 2015). Turkington et al. (2004) reported increased foliar disease when intra-row plant densities were increased. In the same study, fungicide application at BBCH 39 controlled foliar disease at both a high and low intra-row plant densities (Turkington et al., 2004). However, the effect of different foliar fungicide application timings and multiple applications on feed barley yield has not been examined at high plant densities resulting from high seeding rates.

Understanding interactions between seeding rate, post-emergence N, CCC, and foliar fungicide application timing may provide avenues to increase feed barley yield, quality, and input use efficiency in western Canada. These agronomic tools may address feed barley production constraints including N availability at optimal timing for plant uptake, lodging, and foliar disease. The objectives of this study were i) to determine the effect of seeding rate (SR), PGR, and foliar fungicide combinations on grain yield, quality, and agronomic response; ii) to determine if interactions are present between post-emergence N, SR, PGR, and foliar fungicide application timing; and iii) to determine the

effect of environment on grain yield, quality, and agronomic responses to SRxPGRxFungicide combination.

3.2. Materials and Methods

Field experiments were conducted over three growing seasons from 2014-2016 at four rain-fed sites and one irrigated site in the major agro-climatic zones of Alberta, Canada, under no-tillage management (Table 3.1). Soil was sampled prior to seeding (Table 3.2). Growing season precipitation was acquired from the nearest weather station (Table 3.1).

The cultivar selected for the study was the six-row feed cultivar Amisk (Nyachiro, 2013) that has intermediate tolerance to scald [(*Rhynchosporium commune* Zaffarano, McDonald and Linde sp. nov. (formerly known as *Rhynchosporium secalis* (Oudem.) J. J. Davis)] and net form net blotch (*Drechslera* f. *teres* (Sacc.) Shoemaker), moderate resistance to spot form net blotch (*Drechslera teres* f*. maculata* Smedeg.), and very good lodging resistance (Alberta Agriculture and Forestry, 2016a). Amisk was selected in the study because it represented new feed barley genetics and it was promoted as a high yielding, high quality cultivar. All treatments were direct seeded to reach soil moisture (2.5 to 3.8cm seeding depth range) into canola (*Brassica napus* L.) stubble. Seed was treated with difenoconazole {1-(2-[4-(chlorophenoxy)-2-chlorophenyl-(4-methyl-1,3-dioxolan-2-yl)-methyl])-1H-1,2,4-triazole}, metalaxyl [N-(2,6-dimethylphenyl)-N-(methoxyacetyl)-alanine methyl ester], and sedaxane (N-[2-[1,1'-bicyclopropyl]-2-ylphenyl]-3-(difluoromethyl)-1-methyl-1H-pyrazole-4-carboxamide)

formulated as Vibrance XL (Syngenta Canada Inc.). Opener type, fertilizer placement, row spacing, and seeded plot size varied between location and years (Table 3.3). Appropriate seeding fertilizer rates were based on soil test results (Table 3.2) for yield targets based on the land co-operator's 10-year feed barley yield average (Table 3.4). Nitrogen, P, K, and S were applied at seeding as granular fertilizer in the form of urea (46-0-0-0), mono-ammonium phosphate (11-52-0-0), potassium (0-0-60-0), and ammonium sulfate (21-0-0-24) (Table 3.4). Seed safe levels of P were applied in the seed row (22 kg ha^{-1} at Falher, Bon Accord, and Killam; 45kg ha^{-1} at Lethbridge rainfed, and 30kg ha^{-1} at Lethbridge irrigated) and the remaining, if required, was side banded or mid-row banded with the N, K, and S fertilizer. Herbicides were applied pre-emergence and in-crop for weed control (Table 3.5). Insecticide was applied to trial areas as required to control insect pests (Table 3.6). Seeding and harvest dates varied between site and year (Table 3.1). Glyphosate (N-(phosphonomethyl)glycine) was applied pre-harvest at 360 g ae ha^{-1} rate when grain moisture content was < 30% to assist with harvest management.

The experimental design was a strip plot design with post-emergence N rate comprising the horizontal strip (4 levels) and combinations of seeding rate, PGR, and fungicide as the vertical strip (16 levels). The layout of the horizontally oriented plots (horizontal strips) within the trial is indicated in Appendix Figure 1. The sixteen SRxPGRxFung combinations were randomized in vertically oriented plots (vertical strips) running perpendicular to the horizontal strip within each replicate (Appendix Figure 2). Post-emergence N was surface banded as undiluted urea-ammonium nitrate (UAN)

(28% N) with Teejet StreamJet SJ3-015 nozzles just prior to BBCH 30 (Lancashire et al., 1991) at 4 levels: 0 kg N ha^{-1}, 34 kg N ha^{-1}, 64 kg N ha^{-1}, and 34 kg N ha^{-1} with the urease inhibitor N-(n-butyl) thiophosphoric triamide formulated as Agrotain (Koch Agronomic Services, LLC, Wichita, KS) at a rate of 476 ml ha^{-1}. The two seeding rates targeted plant stand densities of 240 and 355 plants m^{-2} and were calculated using grain thousand-kernel weight, germination percent, and predicted seedling mortality (10%). The two PGR levels were control (no PGR application) and chlormequat chloride (CCC) (2-chloroethyl-trimethyl-ammonium chloride), formulated as Manipulator (Taminco US Inc., 2015) applied at BBCH 31-32, at a rate of 2.3 L ha^{-1} and 100 L ha^{-1} water volume. Chlormequat chloride was applied using TeeJet 30-015 nozzles. The four foliar fungicide levels were: i) untreated control (no fungicide); ii) pyraclostrobin {carbamic acid, [2,[[[1-(4-chlorophenyl)-1H-pyrazol-3-yl]oxy]methyl]phenyl]methoxy-,methyl ester} + metconazole [5-[(4-chlorophenyl)methyl]-2,2-dimethyl-1-(1H-1,24-triazol-1-ylmethyl) cyclopentanol] formulated as Twinline (BASF Corporation) applied at BBCH 39 at a rate of 499 mL ha^{-1} (65 g ai ha^{-1} pyraclostrobin; 45 g ai ha^{-1} metconazole); iii) prothioconazole (2-[2-(1-chlorocyclopropyl)-3-(2-chlorophenyl)-2-hydroxypropyl]-1,2-dihydro-3H-1,2,4-triazole-3-thione) + tebuconazole ([1-(4-chlorophenyl)-4,4-dimethyl-3-(1,2,4,j-triazol-1-ylmethyl)pentan-3-ol]-tetrafluoroetho) formulated as Prosaro (Bayer CropScience, Research Triangle Park, NC) applied 2 weeks after BBCH 39 at a rate of 791 mL ha^{-1} (99 g ai ha^{-1} prothioconazole; 99 g ai ha^{-1} tebuconazole) and iv) dual application of Twinline at BBCH 39 and Prosaro 2 weeks later at the same rates listed above. Fungicides were applied with 200 L ha^{-1} water volume using John Deere Twin Air 02 nozzles. Foliar

fungicide levels will be referred to as control, flag, late, and dual, respectively (Table 3.7). Calendar application dates of treatments are listed in Table 3.8. A fungicide application rate error occurred at Killam 2015 and treatment results from this site-year could not be used in the data analysis.

Barley plant stand density was determined 2 weeks after emergence by counting plants in two 1-m row lengths in each plot. Plant height was determined after BBCH 83 by measuring the height of 4 main tillers from the inner plot rows from the ground to the top of the spike (excluding awns). Main stem spike length was determined at the same time by measuring the distance to the spike base and subtracting it from the distance to the top of the spike, excluding awns. To quantify crop greenness differences between treatments, normalized difference vegetation index (NDVI) was measured using a handheld GreenSeeker (Trimble Navigation Ltd, Sunnyvale, CA) between BBCH 83 and 85. Five flag and 5 penultimate leaf samples were collected from the inner rows of each plot from all treatments in the 2nd replicate 7-10 days after the 2nd fungicide application. The percent leaf area infected by fungal disease was estimated visually and disease symptomology was used to determine causal pathogen species. If disease symptomology was insufficient to determine the pathogen species, the pathogen was plated on 10% V-8 tomato juice agar as per Tekauz (1990) and identified visually using a microscope. Ten main stem heads from each plot were collected at 30 to 40% grain moisture and days to maturity were calculated according to Karamanos et al. (2008). Lodging index (Berry et al., 2003) was measured at physiological maturity. Grain was harvested using Wintersteiger Delta small plot combines (Wintersteiger Inc., Saskatoon,

Canada) with 2012 classic grain gauge automatic weigh systems at physiological maturity and yields were adjusted to a standard grain moisture of 14.8%. Test weight was also adjusted to 14.8% moisture and either automatically determined by the combine weigh system or measured using a GAC 2100 Dickey-john grain moisture tester (Churchill Industries, Minneapolis, MN). Kernel weight (g per thousand kernels) was determined by weighing 500 kernels and multiplying the resulting weight by 2. Grain protein, starch, ADF, and NDF concentrations were determined with a DS2500 near infrared reflectance (NIR) spectrometer (FOSS, Eden Prairie, MN 55344, USA) and adjusted to 14.8% moisture. Nitrogen yield was determined by multiplying grain yield x percent nitrogen in the grain, as determined by NIR analysis. Due to various logistical constraints, not every category of data was collected at each site year.

Data were analyzed using PROC MIXED of SAS version 9.4 (SAS Institute Inc., 2014). Lodging data was transformed using the log10 data transformation to achieve normality, and least significant means were reported as the back-transformed values. Post-emergence N (horizontal strip) and seeding rate, PGR, and fungicide (SRxPGRxFung) combinations (vertical strip) were considered fixed effects. Location by year combinations (14 site-years), replicates within site-years, and site-year interactions with fixed effects were considered random. Exploratory analyses revealed that residual variances were heterogeneous among environments. Variance heterogeneity was modeled for all analyses using a repeated statement for PROC MIXED with the group option set to site-year. By considering site-year and the interactions between site-year and the treatments (fixed effects) as random, future performance of treatments at

untested locations may be inferred, and the large number of site years analyzed (14) facilitated this approach (Yang, 2010).

Environment (site-year) interactions with the SRxPGRxFung treatments were assessed with the Wald Z test to determine if variance estimates were different than zero at an α level of 0.01. The relative size of the variance estimate for the environment by SRxPGRxFung interactions compared with the sum of the variance estimates for all effects including environment was also used to determine the importance of the random environment by treatment interactions (Piepho, 2017). Environment x SRxPGRxFung treatment interactions were considered large if the relative size of the variance estimate for the environment x treatment interaction compared with the sum of the variance estimates for all effects including environment was larger than 10%. When the environment x SRxPGRxFung variance estimates were relatively large or significant, a grouping methodology, as previously described by Francis and Kannenberg (1978), was used to explore treatment responses and variability if the responses were of biological significance. The mean and coefficient of variation (CV) were estimated for treatments across years and replicates. Means were plotted against CV for response variables that had a large or significant environment x SRxPGRxFung variance estimate, and the overall mean of means and CVs were included to categorize the data into four categories: Group I: High mean, low variability; Group II: High mean, high variability; Group III: Low mean, high variability; and Group IV: Low mean, low variability.

Orthogonal contrast statements were used to determine responses to seeding rate, CCC at both seeding rate levels, and foliar fungicide application timing at the

different levels of seeding rate and CCC treatments at an α level of 0.05. Correlation between response variables was determined using Pearson's correlation coefficient.

3.3. Results and Discussion

3.3.1. Environmental conditions

Growing season precipitation and soil types were variable across the 14 environments where trials were conducted, with growing season precipitation including irrigation ranging between 101mm and 502mm (Table 3.1). In 5 environments plant stands were within 7% of target densities and at all other site years, plant stands were sufficient but data were not collected or collected too early (data not shown). The predominant foliar diseases in the study were: net form net blotch (*Drechslera* f. *teres* (Sacc.) Shoemaker); spot form net blotch (*Drechslera teres* f. *maculata* Smedeg.); scald [(*Rhynchosporium commune* Zaffarano, McDonald and Linde sp. nov. (formerly known as *Rhynchosporium secalis* (Oudem.) J. J. Davis)]; spot blotch (*Cochliobolus sativus* (Ito & Kuribayashi) Drechs. ex Dastur.); and occasionally leaf stripe rust; however, disease levels in all environments were low and did not exceed 14% diseased flag and penultimate leaf area in any environment (Table 3.9). These low levels of disease severity agreed with on-farm surveillance work conducted in 19 central Alberta fields in 2013 that found 0-11 and 0-12 percent leaf area diseased (PLAD) caused by scald and net-blotch, respectively (Rauhala and Turkington, 2014). However, earlier surveys conducted in 1996 -1997 found scald and net blotch severity on penultimate leaves

ranged from 0-54 PLAD in 338 commercial barley fields (Turkington et al. 2006), indicating that disease levels are not always low in Alberta environments. Lodging occurred in 3 (Bon Accord 2014 and 2016, and Lethbridge Irrigated 2015) of the 14 site years (data not shown). Environment was a significant or large source of variation for plant height, maturity, grain yield, test weight, N yield, grain starch, ADF, and NDF (Table 3.10). In general, plants were taller, maturity was longer, grain and N yield were higher, and test weight was greater in environments that had above average growing season precipitation, while trends for starch, ADF, and NDF across environments were inconsistent (data not shown).

The size of the variance associated with the environment x SRxPGRxFung interactions was small and not significant for all variables with the exception of NDVI, grain starch, and NDF that had a significant interaction (Table 3.10), indicating that responses to SRxPGRxFung combinations for all variables except NDVI, grain starch, and NDF were consistent across environments. Yield response to fungicide application likely did not vary between environments because disease pressure was low across all environments (Table 3.9).

3.3.2. Interactions between post-emergence N and SRxPGRxFung combinations

Although SRxPGRxFung combination significantly affected most variables, the ANOVA revealed no interactions between post-emergence N and SRxPGRxFung combinations for all response variables except NDF concentration (Table 3.10). There was an overall trend towards slightly decreased NDF with the late and dual fungicide

applications (Table 3.11 and 3.13), especially in the absence of post-emergence N application (data not shown). However, NDF concentration was similar among fungicide treatments in the presence of post-emergence N application (data not shown). Importantly, neither the effects of fungicide application nor the interaction between post-emergence N and fungicide application had agronomically or biologically significant effects on feed barley quality because treatment differences for NDF were extremely small (less than 0.1% absolute NDF concentration).

In contrast to the absence of yield and agronomic interactions between post-emergence N and SRxPGRxFung in this study, western Canadian studies reported an interaction between seeding rate and N rate applied at seeding for lodging. Increasing N rate at seeding (above 60kg ha^{-1} N) resulted in increased barley lodging at 400 seeds m^{-2} but not at 200 seeds m^{-2} (O'Donovan et al., 2011). In the same study, there was no interaction between N rates ranging from 0 to 120 kg ha^{-1} applied at seeding and seeding rate for barley maturity, grain yield, or kernel weight (O'Donovan et al., 2011). In the present study, there was no post-emergence N interaction with SRxPGRxFung for lodging, likely because the very good lodging resistance of cv. Amisk resulted in low levels of lodging (Alberta Agriculture and Forestry, 2016a). The magnitude of lodging in the present study was small (Table 12) and lodging occurred in only 3 of 14 environments (data not shown).

Previous studies have reported interactions between N rate and fungicide in winter wheat, with increasing N rate resulting in higher disease levels and greater yield response (Brinkman et al., 2014; Olesen et al., 2000; 2003). Therefore, it was somewhat

surprising that increasing post-emergence N rate had no effect on barley yield response to fungicide. However, foliar fungicide application resulted in larger winter wheat grain yield responses at higher post-emergence N rates only when disease pressure from powdery mildew (caused by the biotrophic pathogen *Blumeria graminis)* was high, but not when disease pressure was low or when *Septoria tritici* (caused by the semi-biotrophic pathogen *Septoria tritici*) predominated (Olesen et al., 2000). In the present study, disease levels were relatively low, ranging between 0 to 14% diseased leaf area, and necrotrophic pathogens were predominant (Table 3.9). Low foliar disease inoculum levels in the trial sites may have also contributed to the lack of interaction between post-emergence N and SRxPGRxFung. The crop rotation on fields where trials were conducted consisted of canola in the year preceding the trial, and a non-barley species for at least 2 years preceding the trial year in all but two site-years (Lethbridge Rainfed 2014 and Lethbridge Irrigated 2015). Duczek at al. (1999) reported that two overwintering periods significantly reduced inoculum of the barley foliar diseases net blotch [*Pyrenophora teres* Drechs. (anamorph *Drechslera teres* (Sacc.) Shoemaker] and spot blotch [*Cochliobolus sativus* (Ito and Kuribayashi) Drechs. ex Dastur (anamorph *Bipolaris sorokiniana* (Sacc.)]. Additionally, foliar disease reduction resulting from planting non-barley species prior to barley compared to barley directly after barley has been well-documented in the Northern Great Plains (Krupinsky et al., 2004; Turkington et al., 2006; Turkington et al., 2012). Therefore, the low inoculum levels resulting in relatively low disease pressure was likely the main cause for no grain yield interaction between post-emergence N and foliar fungicide.

The SRxPGRxFung results were presented across post-emergence N levels (Table 3.12 and 3.13) because of the absence of statistically or biologically significant interactions between post-emergence N and SRxPGRxFung.

3.3.3. Effect of Seeding Rate

Seeding rate affected all variables except height, lodging, grain yield, N yield, and NDF (Table 3.11). Seeding rate was not expected to affect plant height, and the present findings are consistent with Jedel and Helm (1995) who also reported that seeding rate did not affect barley plant height.

Seeding rate had no effect on lodging (Table 3.11). Western Canadian reports on the effect of seeding rate on lodging in barley are variable. O'Donovan et al. (2012) reported a linear increase in lodging in cv. AC Metcalfe malt barley with increasing seeding rates between 100 and 500 seeds m^{-2} when seeding date was relatively late, but not when seeding date was relatively early (generally before May 15), as was the case in the current study. O'Donovan (2011) reported no effect of seeding rate between 200 and 400 seeds m^{-2} on lodging of two malt barley cultivars. Jedel and Helm (1995) reported increased lodging at higher seeding rates in lodge-prone two-row cultivars but not in six-row cultivars with better lodging resistance. The high (355 plants m^{-2}) seeding rate in the present study may not have resulted in increased lodging compared to the 240 plants m^{-2} rate because the range of seeding rates tested was relatively small compared to other western Canadian studies, the seeding dates were early (before May 15) in most environments (Table 3.1), and the very good lodging resistance of cv. Amisk

feed barley may have negated any effects of seeding rate on lodging within the range of seeding rates tested.

Minimal grain yield increases resulting from seeding rates above 200 plants m^{-2} have been reported in numerous other Western Canadian studies (Jedel and Helm, 1995; McKenzie et al., 2005; O'Donovan et al., 2008; O'Donovan et al., 2009; O'Donovan et al., 2011). The absence of grain yield increases at higher seeding rates can be explained by compensatory effects of increased spikes m^{-2} and decreased kernels $spike^{-1}$ and kernel weight at higher seeding rates (Lafond, 1994b). Conversely, yield reductions at seeding rates above 300 seeds m^{-2} were reported in malt barley under adequate soil moisture conditions (McKenzie et al., 2011; O'Donovan et al., 2012) that were attributed to intraspecific competition for sunlight. The present results suggest that although there was no yield or N yield benefit to seeding above 240 plants m^{-2}, no yield or N yield penalty resulted from seeding cv. Amisk feed barley at 355 plants m^{-2}.

Seeding rate significantly impacted spike length, NDVI, maturity, kernel weight, test weight, protein, starch, and ADF (Table 3.11). Main stem spike length decreased by 3.1% at 355 plants m^{-2} compared to 240 plants m^{-2} seeding rate (Table 3.12). This is likely the result of increased intraspecific competition at higher seeding rates reducing the kernels $spike^{-1}$, as was similarly reported by Lafond (1994b) in spring wheat. The shortened spike length did not translate into reduced grain yield at the 355 plants m^{-2} seeding rate in the present study, likely due to increased main stem spikes m^{-2} as reported by Lafond (1994b).

A 1.2% decrease in kernel weight occurred at the 355 plants m^{-2} seeding rate (Table 3.12). This agreed with other agronomic studies that reported decreasing barley kernel weight with increasing seeding rate (Lafond, 1994b; O'Donovan et al., 2012), and O'Donovan et al. (2011) reported a 3.7% decrease in kernel weight at 400 seeds m^{-2} compared to 200 seeds m^{-2} seeding rate. Opposite to the kernel weight response, test weight significantly increased in response to the higher 355 plants m^{-2} seeding rate, but the effect of seeding rate on test weight was small (1% increase) (Table 3.11). Jedel and Helm (1995) reported a variable effect of seeding rates between 129 to 344 seeds m^{-2} on test weight, with higher seeding rates decreasing test weight in 2 of 3 years increasing test weight in 1 of 3 years. Jedel and Helm suggested the increased test weight at higher seeding rates was due to hastened maturity allowing early fall frosts to be avoided. In the present study, harvest dates were relatively early in all environments (Table 3.1) and no damaging frost events were noted. However, higher seeding rates result in reduced tiller number $plant^{-1}$ (O'Donovan et al., 2011; O'Donovan et al., 2012). The slight increase in test weight at the 355 plants m^{-2} seeding rate may have been caused by proportionately fewer tillers containing spikes with small kernels compared to main culm spikes containing larger and heavier kernels. Because the kernel weight and test weight responses to seeding rate were small in magnitude, increasing the seeding rate by 1.5 times (from 240 to 355 plants m^{-2} target seeding rates) did not have biologically or agronomically meaningful impacts on feed barley yield, test weight, or kernel weight.

As expected, maturity was shortened by an average of 1.3 days at the 355 plants m^{-2} seeding rate compared to 240 plants m^{-2} seeding rate (Table 3.12). Shortened maturity at increasing seeding rates is consistent with the reports of other Western Canadian barley agronomic studies (Jedel and Helm, 1995; O'Donovan et al., 2011; O'Donovan et al., 2012). The significantly lower NDVI at 355 plants m^{-2} compared to the 240 plants m^{-2} seeding rate (Table 3.12), was an indication of the hastened maturity. A small positive correlation between NDVI and maturity (R^2=0.14, *P*<0.001) suggested NDVI response to seeding rate was an indicator of the maturity response to seeding rate (data not shown). The significant environment x SRxPGRxFung variance estimate for NDVI indicated variability in NDVI response to SRxPGRxFung across environments (Table 3.10). Biplot analysis comparing mean and coefficient of variation of SRxPGRxFung combinations showed the 240 plants m^{-2} seeding rate treatments tended to have higher NDVI and less variability compared to the 355 plants m^{-2} treatments (Figure 3.3). The greater NDVI variability in the 355 plants m^{-2} treatments was a result of this seeding rate having NDVI that tended to be more similar to the 240 plants m^{-2} seeding rate in high moisture environments (data not shown).

Grain protein significantly decreased by 1% at the 355 plants m^{-2} seeding rate compared to the 240 plants m^{-2} seeding rate (Table 3.12). This result agrees with previous western Canadian reports of decreased protein with increasing seeding rate in barley (McKenzie et al., 2005; O'Donovan et al., 2011; 2012). The protein decrease did not result in a significant seeding rate effect on N yield (Table 3.11) likely because of the small magnitude of the protein decrease (Table 3.12).

Increasing the seeding rate resulted in a small and significant grain starch concentration increase with a similarly small magnitude ADF concentration decrease (Table 3.11 and 3.12). This inverse trend agrees with Surber et al.(2000) who reported a negative relationship between starch and ADF. Although increased grain starch and decreased ADF concentrations are favourable for feed barley quality (Engstrom et al., 1992; Ovenell-Roy et al., 1998b), the small magnitude of the seeding rate effects on protein, starch, and ADF concentration did not have biologically or agronomically significant importance for feed barley quality.

3.3.4. Effect of chlormequat chloride (CCC)

Orthogonal contrasts revealed CCC affected plant height, grain yield, protein, and starch (Table 3.11). The effect of CCC on spike length, test weight, and ADF depended on seeding rate, which indicated interactions between CCC and seeding rate (Table 3.11). Lodging, NDVI, maturity, kernel weight, N yield, and NDF were unaffected by CCC (Table 3.11). Ma and Smith (1992a) similarly reported no effect of CCC on barley maturity in eastern Canada.

Chlormequat chloride shortened cv. Amisk height by 1.3% or 1cm compared to the control regardless of seeding rate (Table 3.12). However, the small height decrease from CCC application did not correspond to a reduction in lodging (Table 3.11). A study conducted in Finland also reported CCC application at BBCH 31 had small effects on barley height, with a 2cm reduction occurring in 1 of 3 years (Rajala and Peltonen-Sainio, 2008). Ramburan and Greenfield (2007) reported no effect of CCC on barley

height or lodging in all four site-years of the South African study. In Quebec, Canada, height decreases of 6-8% occurred 50% of the time in two of four barley cultivars (Ma and Smith, 1991a). In Ontario, Canada, Clark and Fedak (1977) reported that CCC applied at the 3 to 5 leaf stage resulted in height decreases between 0-10% in over half of the 53 barley cultivars studied, but similar to the present study, the height decrease did not prevent lodging. Wheat was the most responsive crop to CCC in Ontario, Canada, with height decreases of up to 33%, followed by smaller decreases of up to 13% and 14% in barley and oats, respectively (Clark and Fedak, 1977). Our findings agree with trends from other studies that found CCC was not effective at reducing barley plant height or lodging.

Chlormequat chloride increased grain yield at both seeding rates (Table 3.11). The overall 2.2% or 0.15MT ha^{-1} grain yield increase (Table 3.12) was consistent across environments, as indicated by the small and NS environment x treatment variance estimate (Table 3.10). Notably, the grain yield increase occurred in environments with and without lodging (data not shown). Reports of the effect of CCC on barley grain yield are variable. Studies conducted in South Africa, Finland, and Quebec reported grain yield was unaffected by CCC applied at the beginning of stem elongation (Ma and Smith, 1991a; Rajala and Peltonen-Sainio, 2008; Ramburan and Greenfield, 2007). Ramburan and Greenfield (2007) also reported that CCC did not increase grain yield at any seeding rate. Counter to these reports, but similar to this study, Ma and Smith (1992a) reported yield increases of up to 10% in one of two barley cultivars. The grain yield increase observed from CCC application in the present study may be explained by the increase in

spike length at 355 plants m^{-2} or increase in test weight at 240 plants m^{-2} (Table 3.11 and 3.12).

Spike length increased by CCC at the 355 plants m^{-2} seeding rate but not at the 240 plants m^{-2} rate (Table 3.11). Studies examining the effect of CCC on spike length are limited, but CCC resulted in increased kernels $spike^{-1}$ from reduced spikelet primordium abortion (Ma and Smith, 1991b), while Ramburan and Greenfield (2007) reported CCC application at stem elongation in barley did not increase kernels $spike^{-1}$. The 0.1cm increase in spike length from CCC at the 355 plants m^{-2} seeding rate may have been indicative of increased kernels $spike^{-1}$ (Table 3.12).

Chlormequat chloride increased test weight by 0.5 kg hL^{-1} at the 240 plants m^{-2} seeding rate but not at the 355 plants m^{-2} seeding rate (Table 3.11). Previous studies examining the effect of CCC on barley test weight are limited. Because tiller number $plant^{-1}$ increases with decreasing barley seeding rate, (O'Donovan et al., 2011; 2012), it is possible that CCC increased test weight on a larger number of tillers at the 240 plants m^{-2} seeding rate, resulting in a significant test weight response to CCC at the 240 plants m^{-2} rate only. Ma and Smith (1991a) reported a similar differential response of tiller spike and main culm spike kernel weights. Because test weight is an important quality parameter for feed barley (Yang et al., 2013), CCC application may be used to increase the quality of cv. Amisk barley at 240 plants m^{-2} seeding rate.

Kernel weight was not affected by CCC application (Table 3.11). Other studies similarly report no effect of CCC on kernel weight (Ma and Smith, 1992a) or occasionally small decreases in kernel weight (Rajala and Peltonen-Sainio, 2008).

Grain protein concentration decreased by 2% at both seeding rates with CCC application compared to the control (Table 3.12). The decrease in grain protein with CCC application in the present study was likely related to the corresponding increase in grain yield with CCC application (Table 3.11). The lack of N yield response to CCC (Table 3.11) was indicative of the inverse relationship between grain yield and protein.

Chlormequat chloride increased grain starch concentration by less than 1% at both seeding rates (Table 3.11). However, the environment affected starch response to CCC, as indicated by the significant environment x SRxPGRxFung interaction (Table 3.10). Individual site-year analysis revealed CCC increased grain starch in 7 of 14 environments at the 240 plants m^{-2} seeding rate and in 4 of 14 environments at the 355 plants m^{-2} seeding rate, and starch increases occurred in environments with varying levels of growing season precipitation (data not shown). Although statistically interesting, all increases in grain starch concentration in the study were small in magnitude and therefore had no biologically or agronomically significant effects on feed barley quality.

Acid detergent fiber decreased with CCC application at the 240 plants m^{-2} seeding rate only (Table 3.11 and 3.12). Similar to starch concentration response to CCC, the small 2% or 0.1% absolute decrease in ADF (Table 3.12) did not have any marked effect on feed barley quality.

3.3.5. Effect of foliar fungicide

Orthogonal contrast statements showed that foliar fungicide application affected all variables except spike length, test weight, and ADF, and the significance for some

variables depended on seeding rate, CCC application, or both seeding rate and CCC application (Table 3.11). Foliar fungicide slightly reduced height and lodging compared to the untreated control at the 240 plants m^{-2} seeding rate without CCC application (Table 3.11). The small (1cm) height reduction and the small lodging reduction (Table 3.12) are consistent with the findings of Turkington et al. (2015) who also reported statistically but not biologically significant reductions in barley lodging when fungicide was applied at the flag leaf stage (BBCH 39) compared to no fungicide application.

Fungicide application increased crop greenness as measured by NDVI compared to the untreated control at the 240 plants m^{-2} seeding rate, and nearly increased NDVI ($p=0.054$ and $p=0.075$) at the 355 plants m^{-2} seeding rate (Table 3.11). The increased NDVI observed with fungicide treatments compared to the untreated control is likely an indication greener leaves due to reduced foliar disease. Leaf disease assessments showed fungicide treatment had less diseased leaf area compared to the untreated control (Table 3.9). Advanced maturity at the time of NDVI measurement for the 355 plants m^{-2} seeding rate may have been responsible for the lessened significance of fungicide application on NDVI at the higher seeding rate. The timing of fungicide application (flag, late, or dual) did not significantly affect NDVI response, but there was a trend ($p=0.087$) towards higher NDVI for the dual fungicide application compared to the flag and late timings at the 355 plants m^{-2} seeding rate with CCC application (Table 3.11).

The majority of contrast statements showed that fungicide application did not affect maturity (Table 3.11). A single contrast comparing late fungicide timing at the 240

plants m^{-2} without CCC application resulted in lengthened maturity by 0.3 days compared to flag leaf timing (Table 3.12). Turkington et al. (2015; 2004; 2012) also reported small maturity increases with foliar fungicide application in barley. Because of the NS and infrequent small maturity increase in the present study, foliar fungicide did not represent a production constraint in the short growing season of Alberta.

Foliar fungicide application increased grain yield compared to the untreated control regardless of seeding rate or CCC application (Table 3.11) by an average of 3% or 0.20 MT ha^{-1} across fungicide treatments (Table 3.12). Turkington et al. (2012) also reported modest (5%) yield increase resulting from foliar fungicide application in barley when disease severity was low overall. Larger yield increases between 13-19% were reported with foliar fungicide application on cv. Harrington (Kutcher et al., 2011). Harrington barley is susceptible to the major foliar diseases of barley, whereas cv. Amisk has intermediate or moderate resistance to scald, net-form net blotch, and spot-form net blotch (Alberta Agriculture and Forestry, 2016a). The improved genetic disease resistance of cv. Amisk likely reduced the magnitude of the yield response to foliar fungicide application compared to studies examining susceptible cultivars. Additionally, the crop rotation on trial sites (2 or more years of non-barley species prior to the trial year in all but 2 environments) likely resulted in inherently reduced inoculum levels (Duczek et al., 1999) and low disease pressure (Table 3.9) and therefore accounted for the small magnitude yield response to fungicide, similar to the findings of Kutcher et al. (2011). Opposite to the conditions encountered in the present study, in situations where barley production is more intensive, such as when on-farm feed requirements must be

met using a finite land-base or when malt barley is grown frequently in the rotation and is downgraded to feed end-use, the yield benefit of a fungicide would likely be greater. There was no yield difference between flag and late fungicide application timing (Table 11), which suggests fungicide application timing flexibility without yield penalty for 2 weeks after the time of flag leaf emergence under the low foliar disease pressures encountered in the study.

There was an interaction between fungicide and seeding rate caused by differential yield response to dual fungicide between the two seeding rates (Table 3.11). The dual fungicide treatment had 2.3% higher grain yield than the single fungicide applications at the 355 plants m^{-2} seeding rate with CCC application, and there was a strong trend (*P*=0.055) for dual fungicide to similarly increase grain yield significantly by 2.1% compared to the single applications at the 355 plants m^{-2} seeding rate without CCC application (Table 3.11 and 3.13). At the 240 plants m^{-2} seeding rate, there was no yield difference between single and dual fungicide application. The trend (*P*=0.087) towards higher NDVI for the dual fungicide treatment compared flag and late timing at the 355 plants m^{-2} seeding rate with CCC application (Table 3.11) supports the finding of increased yield with dual fungicide application. Higher plant density at the 355 plants m^{-2} seeding rate may have encouraged foliar disease development because smaller distances between plants can result in greater disease inoculum interception and increased dispersal of secondary conidia within the canopy (Burdon and Chilvers, 1982). Higher canopy humidity and plant proximity may have also encouraged disease development at the higher seeding rate. In barley, Turkington et al. (2004) reported

higher net blotch severity with increased intra-row plant densities caused by narrow seed band widths compared to wider seed band widths (spread). Conversely, Jedel and Helm (1995) reported that seeding rates between 129 and 344 seeds m^{-2} did not affect net blotch or scald severity in 2 and 6 row barley cultivars seeded with 0.14m row spacing. The narrow row spacing in the Jedel and Helm (1995) study may have diluted differences in plant density between seeding rate treatments and may have been the cause of the similar disease severity between seeding rates. In the present study, higher plant density caused by higher seeding rate likely resulted in increased disease pressure that caused the larger magnitude yield response to the dual fungicide treatment compared to single applications. Therefore, dual fungicide application increased yield at higher seeding rates compared to single applications, but there was no yield benefit for dual compared to a single fungicide application at moderate (240 plants m^{-2}) seeding rates.

Kernel weight increased in response to fungicide application compared to the control across all seeding rates and PGR treatments (Table 3.11). The 2% increase in kernel weight was small (Table 3.13), and in agreement with the findings of Turkington et al. (2012) that reported a foliar fungicide application at flag leaf emergence in AC Metcalfe malt barley resulted in a small (2%) kernel weight increase. Larger kernel weight increases, between 4 and 24%, in response to foliar fungicide application have been reported for disease susceptible cultivars such as cv. Harrington (Bailey et al., 2000; Turkington et al., 2004). While cv. Harrington is susceptible to the major foliar diseases of barley in Alberta, cv. Amisk in the present study has improved genetic

disease resistance. Kernel weight was higher for late fungicide application timing compared to flag leaf timing (Table 3.11 and 3.13). The higher test weight for late timing may have been a result of fungicide application to the emerged spike.

Orthogonal contrast statements showed the effect of foliar fungicide application on grain protein, N yield, and grain starch was infrequent (Table 3.11) and small in magnitude (Table 12). More frequent effects occurred for grain NDF (Table 3.11) with small decreases in NDF concentration resulting from late or dual fungicide applications (Table 3.13). Similar to other quality parameters, the magnitude of responses was small and not of biological significance.

3.4. Conclusion

Yield gains related to seeding rate in isolation did not occur above the moderate seeding rate (240 plants m^{-2}) and this occurred in both irrigated and rainfed environments. There were small added benefits of increased test weight and reduced days to maturity observed with the higher 355 plants m^{-2} seeding rate. An interaction between seeding rate and dual fungicide applications required the higher 355 plants m^{-2} seeding rate for maximum yield.

Grain yield increased by 2.2% with CCC application, a result of altering different yield components depending on the seeding rate. At the 240 plants m^{-2} seeding rate, the CCC yield increase was achieved through an increase in test weight, but at the 355 plants m^{-2} seeding rate, the CCC yield increase was achieved by an increase in spike length. Seeding rate did not affect the overall grain yield response to CCC.

Foliar fungicide application increased grain yield compared to the untreated control by an average of 3% in the low disease pressures encountered in the 14 irrigated and rainfed site-years of the study. There was no difference in grain yield between flag leaf and late (spike emergence) fungicide timing, which indicates application flexibility after the time of flag leaf emergence. The late fungicide application resulted in higher kernel weight. Yield response to dual fungicide applications compared to a single application depended on seeding rate. Dual fungicide applications increased yield compared to a single application by 2% only at the higher 355 plants m^{-2} seeding rate, and there was no difference between single and dual applications at the 240 plants m^{-2} seeding rate. Therefore, seeding rate should be considered when applying dual fungicide applications to optimize grain yield. The small responses to foliar fungicide application in this study may be attributed to both the genetic disease resistance of cv. Amisk feed barley and also the agronomically sound previous crop rotation resulting in low disease pressure at the irrigated and rainfed experimental sites. These results may be reflective of on-farm response to foliar fungicides, if a cultivar that is genetically resistant to foliar disease is grown, because the preceding crop rotation at trial sites within the study was reflective of the predominant (86%) on-farm barley rotation between 2007-2010 which was barley 1 in every 4 years or 1 in every 3 years, (personal communication, Julia Leeson, 2017). Higher disease conditions, which were not encountered in the present study, may result in greater response to foliar fungicides. Therefore, the in-season decision to apply a foliar fungicide demands that producers and agronomists consider their feed barley cultivar selection and previous crop rotation in the field.

Chlormequat chloride had little effect on height and no effect on lodging reduction in cv. Amisk feed barley in both irrigated and rainfed environments. The efficacy of CCC on barley height reduction and lodging reduction was not improved at the higher 355 plant m^{-2} seeding rate. Genetic resistance to lodging is currently the most effective method available for producers to address lodging pressure in barley.

Agronomic management (seeding rate, CCC, and foliar fungicide) did not markedly improve feed barley protein or grain quality based on starch, or ADF and NDF concentration.

Highest cv. Amisk feed barley yields required the combination of: a seeding rate of 355 plants m^{-2}, CCC application, and dual fungicide applications. The yield increase associated with these high-input level combined practices was relatively small (0.46 MT ha^{-1} or 6.8%) compared to the low-input combination of a seeding rate of 240 plants m^{-2} , no CCC application, and no fungicide application, under the low disease pressures encountered in the study environments. Best management practices such as: growing cultivars with excellent standability and genetic resistance to fungal diseases and following diverse crop rotations (to reduce foliar disease pressure) are recommended to optimize yield and agronomic performance in feed barley production. Barley was grown in 52% of 223 surveyed fields in Alberta between 2007-2010, and of these fields that grew barley, the most common barley frequencies in the crop rotation, occurring in 58% and 27% of fields, was barley every 1 in 4 years and every 1 in 3 years, respectively (personal communication, Julia Leeson, 2017). This on-farm barley rotation is representative of the infrequent planting of barley in the 2 years prior to study

environments that discouraged fungal disease development. Therefore, under these conditions, similarly modest on-farm yield gains may be expected from high input practices such as a higher seeding rate, CCC application, and dual foliar fungicide applications, when a cultivar that is genetically resistant to foliar diseases is grown.

Table 3-1. Soil classification, seeding date, harvest date, growing season precipitation, and site coordinates for each environment (site-year).

Location	Year	Coordinates	Great Group classification	Canadian equivalent	Seeding date	Harvest date	Observed precipitation†	Long-term mean precipitation ††
							mm	
Bon Accord	2014	53°48'N 113°28'W	Udic Boroll	Black Chernozem	9 May	4 Sept	181	344
Rainfed	2015	53°48'N 113°27'W	Udic Boroll	Black Chernozem	27 April	31 Aug	121	
	2016	53°55'N 113°27'W	Udic Boroll	Black Chernozem	28 April	8 Sept	323	
Falher	2014	55°48'N 117°11'W	Boraf	Gray Luvisol	22 May	30 Aug	101	301
Rainfed	2015	55°47'N 117°10'W	Boraf	Gray Luvisol	14 May	3 Sept	155	
	2016	55°40'N 117°2' W	Boraf	Gray Luvisol	10 May	15 Sept	338	
Killam	2014	52°48'N 111°52'W	Udic Boroll	Black Chernozem	24 May	25 Aug	263	309
Rainfed	2016	52°51'N 111°53'W	Udic Boroll	Black Chernozem	16 May	14 Sept	345	
Lethbridge	2014	49°22'N 112°55'W	Typic Boroll	Dark Brown Chernozem	1 May	16 Sept	426	317
irrigated	2015	49°41'N 112°39'W	Typic Boroll	Dark Brown Chernozem	24 April	12 Aug	282	
	2016	49°42'N 112°31'W	Typic Boroll	Dark Brown Chernozem	11 April	17 Aug	502	
Lethbridge	2014	50°33'N 113°53'W	Udic Boroll	Black Chernozem	16 May	17 Sept	326	305
Rainfed	2015	49°22'N 112°55'W	Typic Boroll	Dark Brown Chernozem	17 April	5 Aug	116	
	2016	49°40'N 112°31'W	Typic Boroll	Dark Brown Chernozem	13 April	16 Aug	251	

† Observed precipitation from seeding to harvest. This includes precipitation and irrigation at Lethbridge Irrigated site

‡ Calculated from April 1 to Sept 15 using 30 year historical data interpolated from the nearest geographical provincial weather station (Alberta Agriculture and Forestry, 2016).

Table 3-2. Soil descriptions and nutrient properties before fertilizer application at two sample depths for each site-year.

Site	Year	Soil Properties													
		pH		CEC†		OM‡		NO_3–N§		P¶		K#		S††	
		Sample Depth‡‡													
		cm													
		0-15	16-30	0-15	16-30	0-15	16-30	0-15	16-30	0-15	16-30	0-15	16-30	0-15	16-30
				--cmol kg^{-1}--		------%------		----------mg kg^{-1}----------							
Bon Accord	2014	6.3	6.9	23.2	22.5	9.6	5.0	10	16	21	19	167	107	32	118
Rainfed	2015	5.4	6.4	26.4	23.5	8.7	6.3	9	1	24	12	218	129	16	11
	2016	5.1	5.8	26.6	17.5	7.0	5.6	20	5	18	16	107	89	23	15
Falher	2014	6.1	6.9	13.2	19.1	4.8	2.3	10	10	24	-	226	176	15	14
Rainfed	2015	5.7	6.2	9.1	14.8	2.7	2.4	20	17	17	0	106	96	10	12
	2016	5.6	5.8	17.1	22.8	5.3	3.1	11	8	30	8	244	114	16	14
Killam	2014	5.1	6.0	15.1	10.6	4.5	2.4	11	8	48	20	261	112	18	16
Rainfed	2016	5.3	5.6	16.9	17.8	5.2	3.0	12	5	37	20	228	104	19	13
Lethbridge	2014	7.9	8.1	35.2	39.8	4.2	2.7	8	26	9	5	251	265	11	25
Irrigated	2015	7.5	7.8	31.8	40.4	3.8	3.1	13	26	39	14	330	299	18	40
	2016	7.2	7.7	28.9	34.1	3.4	2.7	18	16	31	14	345	379	17	47
Lethbridge	2014	6.9	7.5	24.8	37.8	4.2	2.7	1	2	15	6	348	262	16	29
Rainfed	2015	7.7	7.8	43.3	44.5	3.9	2.9	6	9	7	2	350	303	8	21
	2016	6.9	7.7	24.5	34.0	3.0	2.2	7	7	16	11	385	376	26	95

† Cation exchange capacity
‡ Soil organic matter
§ Nitrate nitrogen
¶ Phosphorus (bray)
# Potassium
†† Sulfur
‡‡ 0-15 and 15-60cm at Lethbridge irrigated and rainfed sites.

Table 3-3. Seeding equipment and plot area information for each site-year.

Site	Year	Seed Drill Type	Opener Type	Fertilizer Placement	Row Spacing	Number of Rows	Seeded Plot area
					---m---		----m^{-2}---
Bon Accord	2014	Air seeder	Atom Jet hoe	Side band†	0.20	8	10.9
Rainfed	2015	No-till box seeder	Double disc	Mid-row band‡	0.25	6	10.2
	2016	No-till box seeder	Double disc	Mid-row band	0.25	6	10.2
Falher	2014	No-till box seeder	Double shoot hoe	Side band	0.23	6	11.7
Rainfed	2015	Air seeder	Double shoot hoe	Side band	0.23	6	11.7
	2016	Air seeder	Double shoot hoe	Side band	0.23	6	11.7
Killam	2014	Air seeder	Atom Jet hoe	Side band	0.20	8	10.9
Rainfed	2016	No-till box seeder	Double disc	Mid-row band	0.25	6	10.2
Lethbridge	2014	No-till box seeder	John Deere 90 series disc	Side band	0.25	8	20.0
Irrigated	2015	No-till box seeder	John Deere 90 series disc	Side band	0.25	8	20.0
	2016	No-till box seeder	John Deere 90 series disc	Side band	0.25	8	20.0
Lethbridge	2014	No-till box seeder	John Deere 90 series disc	Side band	0.25	8	20.0
Rainfed	2015	No-till box seeder	John Deere 90 series disc	Side band	0.25	8	20.0
	2016	No-till box seeder	John Deere 90 series disc	Side band	0.25	8	20.0

† Side banding placed fertilizer 5cm to the side and 2cm below the seed

‡ Mid-row banding placed fertilizer 12.5cm to the side and 4cm below the seed

Table 3-4. Yield targets and fertilization rates of nitrogen, phosphorous, potassium, and sulfur applied at seeding for each environment.

			Nutrient Applied			
Site	Year	Yield target†	N‡	P_2O_5§	K_2O¶	S#
		---MT ha^{-1}---	----------kg ha^{-1}----------			
Bon Accord	2014	4.8	88	50	22	17
Rainfed††	2015	4.8	120	50	22	0
	2016	4.8	102	34	67	5.5
Falher	2014	4.5	108	56	22	22
Rainfed	2015	4.5	90	34	28	28
	2016	4.5	68	39	22	17
Killam	2014	5.6	130	22	22	5
Rainfed	2016	5.6	161	17	22	6
Lethbridge	2014	6.3	123	55	0	0
Irrigated	2015	5.5	66	30	0	0
	2016	5.5	81	35	0	0
Lethbridge	2014	3.8	95	25	0	0
Rainfed	2015	3.8	75	45	0	0
	2016	3.8	77	35	0	0

†Yield goals are based on the land cooperator's 10-year on-farm feed barley yield average in each environment
‡Nitrogen
§Phosphorus
¶Potassium
#Sulfur
††Co-operator had no record of feed barley yield and so their long term malt barley yield average was adjusted for the differential between the AFSC (Agriculture Financial Services Corporation, 2014) Risk Area yield average for feed and malt barley.

Table 3-5. Pre-emergence and in-crop herbicide active ingredients, application dates, and application rates for weed control in 14 site-years.

Site	Year	Pre-emergence weed control		In-crop weed control	
		Active ingredients	Application date	Active ingredients	Application date
Bon Accord	2014	Glyphosate†, saflufenacil‡	13 May	Florasulam§, fluroxypyr¶, MCPA ester#, pinoxaden††	11 June
Rainfed	2015	Glyphosate, saflufenacil	4 May	Florasulam, fluroxypyr, MCPA ester, pinoxaden	5 June
	2016	Glyphosate, saflufenacil	4 May	Florasulam, fluroxypyr, MCPA ester, pinoxaden	31 May
Falher	2014	Glyphosate, saflufenacil	21 May	Fluroxypyr, clopyralid‡‡, pinoxaden	14 June
Rainfed	2015	Glyphosate	6 May	Florasulam, fluroxypyr, MCPA ester, pinoxaden	8 June
	2016	Glyphosate, tribenuron-methyl§§	2 May	Florasulam, fluroxypyr, MCPA ester, pinoxaden	5 June
Killam	2014	Glyphosate, tribenuron-methyl	23 May	Florasulam, fluroxypyr, MCPA ester, pinoxaden	12 June
Rainfed	2016	Glyphosate, saflufenacil	13 May	Florasulam, fluroxypyr, MCPA ester, pinoxaden	18 June
Lethbridge	2014	Glyphosate, saflufenacil	28 April	Florasulam, MCPA ester, pinoxaden	6 June
Irrigated	2015	Glyphosate, saflufenacil	21 April	Florasulam, MCPA ester, pinoxaden	27 May
	2016	Glyphosate, saflufenacil	8 April	Florasulam, MCPA ester, pinoxaden	16 May
Lethbridge	2014	Glyphosate, saflufenacil	13 May	Florasulam, MCPA ester, pinoxaden	23 June
Rainfed	2015	Glyphosate, saflufenacil	15 April	Florasulam, MCPA ester, pinoxaden	25 May
	2016	Glyphosate, saflufenacil	18 April	Florasulam, MCPA ester, pinoxaden	25 May

† Glyphosate applied at 360 g ae ha^{-1} rate
‡ Saflufenacil applied at 18 g ha^{-1} rate
§ Florasulam applied at 2.5 g ha^{-1} rate
¶ Fluroxypyr applied at 99 g ha^{-1} rate at all site-years except Falher 2014 where it was applied at 140 g ae ha^{-1} rate
# MCPA ester applied at 356 g ha^{-1} rate
†† Pinoxaden applied at 61 g ha^{-1} rate
‡‡Clopyralid applied at 99 g ha^{-1} rate
§§Tribenuron-methyl applied at 7.4 g ha^{-1} rate

Table 3-6. Insecticide active ingredient, application rate, and application date at site-years requiring insect pest control in the trial area.

Site	Year	Insect controlled	Active ingredient applied	Application rate	Application date
				-----g ae ha^{-1}-----	
Bon Accord	2015	*Melanoplus* spp.	Chlorpyrifos†	396	15 June
Bon Accord	2016	*Oulema melanopus* L.	Malathion‡	556	23 June
Bon Accord	2016	*Melanoplus* spp.	Chlorpyrifos	396	18 July
Falher	2016	*Euxoa* spp.	Chlorpyrifos	117	14 June

† (*O, O*-diethyl *O*-3,5,6-trichloro-2-pyridinyl phosphorothioate)

‡ 2-[(dimethoxyphosphorothioyl)sulfanyl]butanedioate

Table 3-7. Treatment structure for 16 levels of seeding rate, plant growth regulator, and fungicide combination (SRxPGRxFung) fixed effect.

SRxPGRxFung level	Seeding rate	Plant growth regulator	Foliar fungicide timing
	plants m^{-2}		
1	240	control	control
2	240	CCC†	control
3	240	CCC	flag‡
4	240	CCC	late§
5	240	CCC	dual¶
6	240	control	flag
7	240	control	late
8	240	control	dual
9	355	control	control
10	355	CCC	control
11	355	CCC	flag
12	355	CCC	late
13	355	CCC	dual
14	355	control	flag
15	355	control	late
16	355	control	dual

† Chlormequat chloride applied at BBCH 31-32

‡ Pyraclostrobin + metconazole formulated as Twinline applied at BBCH 39

§ Prothioconazole + tebuconazole formulated as Prosaro applied two weeks after BBCH 39

¶ Twinline applied at BBCH 39 and Prosaro applied two weeks after BBCH 39

Table 3-8. Plant growth regulator and foliar fungicide treatment application dates at 14 site-years.

Location	Year	Treatment		
		Plant growth regulator†	Flag fungicide‡	Late fungicide §
		----------Application date----------		
Bon Accord	2014	18 June	2 July	15 July
Rainfed	2015	13 June	26 June	10 July
	2016	10 June	23 June	7 July
Falher	2014	27 June	4 July	16 July
Rainfed	2015	18 June	6 July	13 July
	2016	22 June	1 July	13 July
Killam	2014	26 June	4 July	16 July
Rainfed	2016	24 June	7 July	21 July
Lethbridge	2014	13 June	2 July	10 July
Irrigated	2015	5 June	19 June	2 July
	2016	1 June	13 June	28 June
Lethbridge	2014	25 June	11 July	22 July
Rainfed	2015	9 June	18 June	2 July
	2016	1 June	23 June	6 July

† Chlormequat chloride applied at BBCH 30-31

‡ Pyraclostrobin + metconazole applied at BBCH 39 for flag and dual fungicide treatments

§ Prothioconazole + tebuconazole applied approximately 2 weeks after BBCH 39 for flag and dual fungicide treatments

Table 3-9. Diseases present and percent fungal diseased leaf area 4 weeks after BBCH 39 on the upper 2 leaves for fungicide treatments† in the 2nd replicate in 14 Alberta environments.

		Percent leaf area diseased‡				
		Fungicide application timing				Fungal diseases
Site	Year	Control	Flag	Late	Dual	present¶
		----------%----------				
Bon Accord	2014	-§	-	-	-	NF
Rainfed	2015	3	2	1	1	SR
	2016	9	2	3	1	NF, SC, SR
Falher	2014	-	-	-	-	None
Rainfed	2015	3	2	2	1	SF, SR
	2016	4	2	1	1	NF, SB
Killam	2014	-	-	-	-	NF, SF, SC
Rainfed	2016	11	4	4	3	NF, SC, SR
Lethbridge	2014	-	-	-	-	NF, SF, SR
Irrigated	2015	6	2	0	2	SF, SR
	2016	14	3	4	3	NF, SF, SR
Lethbridge	2014	-	-	-	-	NF, SR
Rainfed	2015	7	4	2	3	SF, SR
	2016	10	4	4	2	NF, SR

† Leaves were sampled from plots with 355 plants m^{-2} seeding rate, control CCC, and 34 kg ha^{-1} post-emergence N.

‡ Average total diseased area of 5 flag and 5 penultimate leaves per treatment. Recorded in 2015 and 2016 only

¶ NF= net-form net blotch, SF= spot-spot form net blotch, SB=spot blotch, SC= scald, SR= stripe rust

§ Dash indicates data not collected

Table 3-10. *P* values and variance estimates from the ANOVA for the effect of seeding rate, plant growth regulator, and foliar fungicide (SRxPGRxFung) treatment combination and the interaction with post-emergence nitrogen (N) on feed barley agronomic variables collected at 14 Alberta environments. Environments (location and year), replicates within environments and their interactions with fixed effects were considered random.

Effects	Spike length	NDVI†	Height	Lodging‡	Maturity	Grain yield	Kernel weight	Test weight	Grain protein	N yield	Grain starch	ADF§	NDF¶
	cm		cm		days	MT ha^{-1}	g	kg hL^{-1}	mg g^{-1}	kg ha^{-1}	----------%----------		
SRxPGRxFung	**<0.001**	**<0.001**	**0.004**	0.237	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.055.	**<0.001**	**<0.001**	**<0.001**
(SRxPGRxFung) x N	0.641	0.884	0.341	0.728	0.147	0.175	0.113	0.967	0.071	0.665	0.640	0.510	**0.050**
Environment (E)#	<1	<1	101**	<1	56	2**	7	7*	1**	882**	<1**	<1**	<1**
E x (SRxPGRxFung)††	<1	2**	<1	2	<1	<1	1	<1	<1	<1	1**	<1	1**
Adjusted CV (%)	8.9	6.1	4.5	21.3	1.2	6.4	2.8	2.1	4.0	7.5	1.7	3.1	1.8

† Normalized difference vegetation index

‡ Lodging index of 0-100, where 0= upright and 100=completely lodged (Berry et al., 2003). Lodging data was transformed using log10 transformation to achieve normality

§ Acid detergent fiber

¶ Neutral detergent fiber

Variance estimates for the environment random effect.

†† Percentage of the variance associated with the environment × SRxPGRxFung calculated as follows: [(variance estimate for environment X SRxPGRxFung)/(sum of all variance estimates including environment)]x 100.

** *P*-value <0.01

Table 3-11. *P* values from orthogonal contrast statements for foliar fungicide application timing (control, early, late, dual) at two seeding rates (240 and 355 plants (pl) m^{-2}) on feed barley agronomic variables. Site-year (environment), replicates within site-year, and replicate within site year interaction with fixed effects were considered random.

Contrast statement	Spike length	NDVI†	Height	Lodging	Maturity	Grain yield	Kernel weight	Test weight	Grain protein	N yield	Grain starch	ADF	NDF
	cm		cm		days	MT ha^{-1}	g	kg hL^{-1}	mg g^{-1}	kg ha^{-1}	---------- % ----------		
240 vs. 355 plants m^{-2}	**<0.001**	**<0.001**	0.184	0.896	**<0.001**	0.374	**<0.001**	**<0.001**	**<0.001**	0.185	**<0.001**	**<0.001**	0.294
CCC‡ vs. NPGR§ (240 pl m^{-2})	0.768	0.119	**0.016**	0.665	0.375	**<0.001**	0.121	**<0.001**	**<0.001**	0.582	**<0.001**	**0.004**	0.338
CCC vs. NPGR (355 pl m^{-2})	**0.034**	0.937	**<0.001**	0.850	0.278	**<0.001**	0.794	0.442	**<0.001**	0.479	**0.015**	0.722	0.861
240 plants m^{-2}, NPGR													
Fungicide¶ vs. NF#	0.818	**0.045**	**0.035**	**0.026**	0.146	**0.018**	**<0.001**	0.547	0.122	0.311	0.440	0.498	0.135
Flag††vs. late‡‡	0.384	0.715	0.185	0.412	**0.037**	0.343	**0.021**	0.916	0.670	0.181	0.458	0.893	0.081
Dual§§ vs. [flag + late]	0.621	0.812	0.131	0.874	0.424	0.645	0.356	0.319	0.075	0.156	0.240	0.218	0.082
240 plants m^{-2}, CCC													
Fungicide vs. NF	0.489	**0.009**	0.480	0.873	0.387	**0.001**	**<0.001**	0.388	0.406	**0.028**	0.321	0.387	**0.028**
Flag vs. late	0.544	0.562	0.132	0.068	0.288	0.074	**<0.001**	0.186	0.609	0.057	0.141	0.123	0.074
Dual vs. [flag + late]	0.270	0.509	0.504	0.409	0.206	0.112	**0.017**	0.106	0.427	0.389	**0.019**	0.197	0.147
355 plants m^{-2}, NPGR													
Fungicide vs. NF	0.151	0.054	0.510	0.177	0.150	**0.004**	**<0.001**	0.217	**0.012**	0.386	0.549	0.774	0.193
Flag vs. late	0.369	0.811	0.463	0.850	0.282	0.140	0.321	0.075	0.500	0.330	0.166	0.236	**0.018**
Dual vs. [flag + late]	0.980	0.343	0.399	0.223	0.473	0.055	**0.029**	0.961	0.142	0.506	0.084	0.570	**0.015**
355 plants m^{-2}, CCC													
Fungicide vs. NF	0.843	0.075	0.233	0.069	0.064	**0.003**	**<0.001**	0.225	0.291	0.077	0.657	0.312	0.124
Flag vs. late	0.823	0.306	0.572	0.577	0.150	0.600	**0.002**	0.670	0.867	0.979	0.529	0.332	**0.019**
Dual vs. [flag + late]	0.097	0.087	0.344	0.165	0.894	**0.033**	0.410	0.341	0.982	0.077	0.720	0.308	0.497

† Refer to Table 3-10 for response variable descriptions

‡ Chlormequat chloride applied at BBCH 31

§ Control plant growth regulator treatment

¶ Flag, late, and dual fungicide treatments.

Control fungicide treatment

†† Flag fungicide treatment of Twinline (pyraclostrobin + metconazole) applied at BBCH 39

‡‡ Late fungicide treatment of Prosaro (prothioconazole + tebuconazole) applied 2 weeks after BBCH 39

§§ Dual fungicide treatment of Twinline applied at BBCH 39 and Prosaro applied two weeks later

Table 3-12. LS means of seeding rate and PGR treatments for response variables across 14 site-years.

Treatment	Spike length	NDVI†	Height	Lodging	Maturity	Grain yield	Kernel weight	Test weight	Grain protein	N yield	Grain starch	ADF	NDF
	cm		cm		days	MT ha^{-1}	g	kg hL^{-1}	mg g^{-1}	kg ha^{-1}	----------%----------		
240 pl m^{-2}	6.3	0.429	71.9	11	99.0	6.93	44.9	63.6	112	132	59.8	5.8	18.8
355 pl m^{-2}	6.1	0.402	71.6	11	97.7	6.96	44.3	63.9	111	131	59.9	5.7	18.8
NPGR‡ at 240 pl m^{-2}	6.3	0.433	72.3	12	98.9	6.86	45.0	63.3	113	132	59.7	5.8	18.8
CCC¶ at 240 pl m^{-2}	6.3	0.425	71.5	11	99.0	7.00	44.8	63.8	111	132	59.9	5.7	18.8
NPGR at 355 pl m^{-2}	6.1	0.402	72.1	11	97.6	6.88	44.3	63.9	112	131	59.9	5.7	18.8
CCC at 355 pl m^{-2}	6.2	0.402	71.0	11	97.8	7.03	44.3	64.0	110	131	60.0	5.7	18.8
ddf§	195	135	195	30	120	195	135	165	195	195	195	195	195

†Refer to Table 3-10 for response variable descriptions

‡ Control plant growth regulator treatment

¶ Chlormequat chloride applied at BBCH 31

§ Denominator degrees of freedom

Table 3-13. LS means of fungicide treatments at seeding rate and PGR combinations for response variables across 14 site-years.

Treatment	Spike length	NDVI†	Height	Lodging	Maturity	Grain yield	Kernel weight	Test weight	Grain protein	N yield	Grain starch	ADF	NDF
	cm		cm		days	MT ha^{-1}	g	kg hl^{-1}	mg g^{-1}	kg ha^{-1}	----------%----------		
240 pl m^{-2}, NPGR‡													
NF§	6.3	0.420	73.1	17	98.7	6.73	44.3	63.2	114	131	59.6	5.8	18.8
Fungicide¶	6.3	0.437	72.0	10	99.0	6.90	45.2	63.3	113	132	59.7	5.8	18.8
Flag#	6.4	0.434	71.8	9	98.6	6.87	44.8	63.4	113	132	59.7	5.8	18.8
Late††	6.3	0.438	72.7	11	99.2	6.95	45.4	63.4	114	134	59.6	5.8	18.8
Dual‡‡	6.3	0.438	71.4	9	99.1	6.87	45.3	63.1	112	131	59.7	5.7	18.7
240 pl m^{-2}, CCC§§													
NF	6.3	0.408	71.8	10	98.9	6.83	44.3	63.6	112	130	59.8	5.7	18.8
Fungicide	6.3	0.430	71.4	11	99.0	7.06	44.9	63.8	111	133	59.9	5.7	18.8
Flag	6.3	0.425	71.0	7	98.8	6.94	44.3	63.5	111	131	59.8	5.8	18.8
Late	6.4	0.431	72.0	13	99.1	7.10	45.2	63.9	112	134	59.9	5.7	18.7
Dual	6.3	0.434	71.1	12	99.2	7.14	45.3	64.1	112	134	60.0	5.7	18.7
355 pl m^{-2}, NPGR													
NF	6.1	0.391	72.4	13	97.4	6.73	43.8	64.1	113	130	59.8	5.7	18.8
Fungicide	6.1	0.406	72.0	10	97.7	6.93	44.5	63.8	112	131	59.9	5.7	18.8
Flag	6.1	0.395	71.6	10	97.5	6.82	44.2	63.5	112	130	59.8	5.7	18.8
Late	6.1	0.406	72.1	11	97.8	6.95	44.4	64.1	112	132	59.9	5.7	18.7
Dual	6.1	0.416	72.4	8	97.8	7.03	44.8	63.8	111	132	60.0	5.7	18.7
355 pl m^{-2}, CCC													
NF	6.2	0.390	71.5	15	97.5	6.87	43.8	64.2	111	129	59.9	5.7	18.8
Fungicide	6.1	0.406	70.9	10	97.9	7.08	44.5	63.9	110	132	60.0	5.7	18.8
Flag	6.1	0.402	71.2	10	97.7	7.01	44.0	63.9	110	131	59.9	5.7	18.8
Late	6.1	0.404	70.9	12	98.1	7.05	44.7	63.8	110	131	60.0	5.7	18.7
Dual	6.2	0.411	70.5	7	97.8	7.19	44.8	64.1	110	134	60.0	5.7	18.7

† Refer to Table 3-10 for response variable descriptions

‡ Control plant growth regulator treatment

§ Control fungicide treatment

¶ Average LS mean of flag, late, and dual fungicide treatments.

Flag fungicide treatment of Twinline applied at BBCH 39

†† Late fungicide treatment of Prosaro applied 2 weeks after BBCH 39

‡‡ Dual fungicide treatment of Twinline applied at BBCH 39 and Prosaro applied two weeks after BBCH 39

§§ Chlormequat chloride applied at BBCH 31

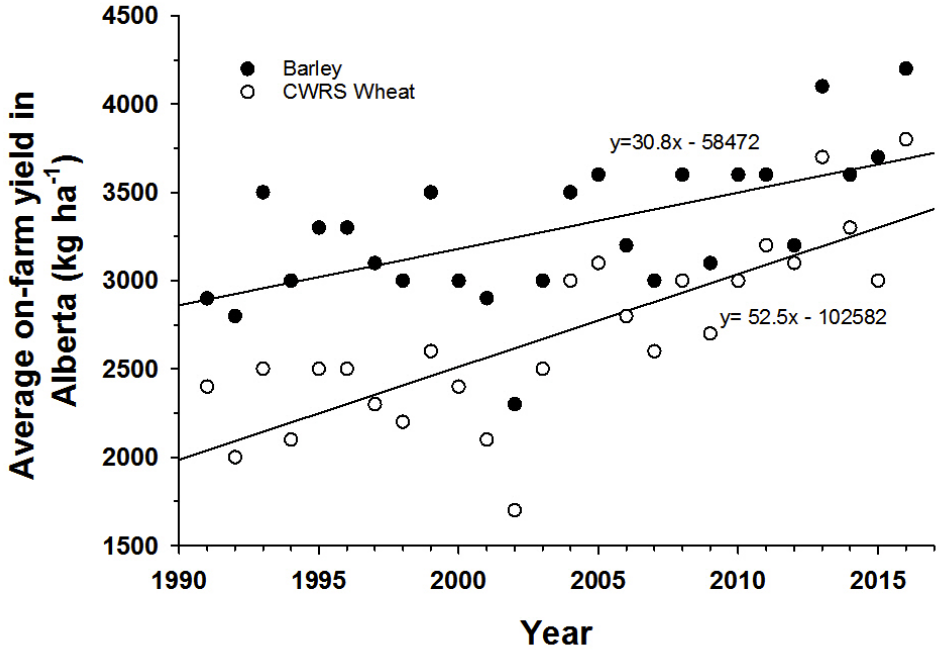

Figure 3-1. Average grain yields of barley and Canada western red spring (CWRS) wheat for 15 years (1991-2016) in Alberta on-farm production adapted from Statistics Canada (2017).

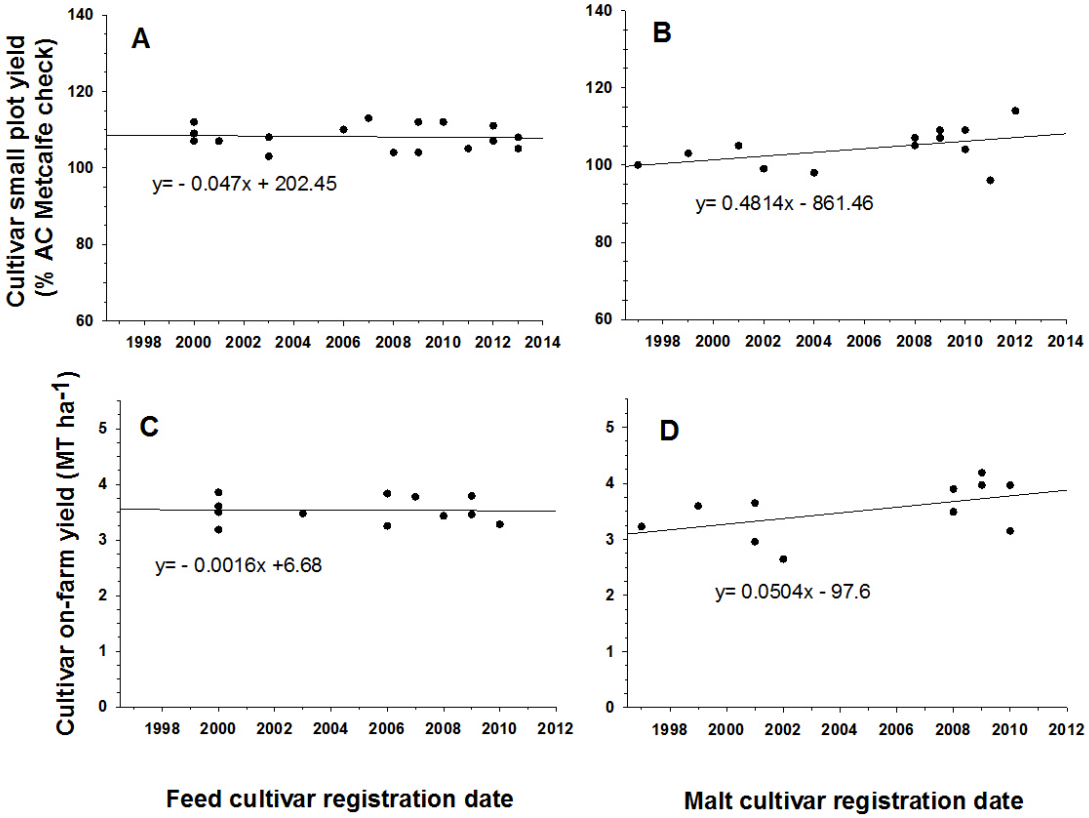

Figure 3-2. (A) Performance of hulled two-row and six-row feed barley cultivars registered between 1997 and 2013 tested in the Alberta Regional Variety small-plot trials. Adapted from Alberta Agriculture and Forestry (2016a). (B) Performance of hulled two-row and six-row malt barley cultivars registered between 1997 and 2013 tested in the Alberta Regional Variety small-plot trials. Adapted from Alberta Agriculture and Forestry (2016a). (C) Six-year average on-farm grain yield of hulled two-row and six-row feed barley cultivars registered between 1997 and 2010 under Alberta rain-fed production for the 2010-2015 growing seasons. Adapted from Agriculture Financial Services Corporation (2016). (D) Six-year average on-farm grain yield of hulled two-row and six-row malt barley cultivars registered between 1997 and 2010 under Alberta rain-fed production for the 2010-2015 growing seasons. Adapted from Agriculture Financial Services Corporation (2016).

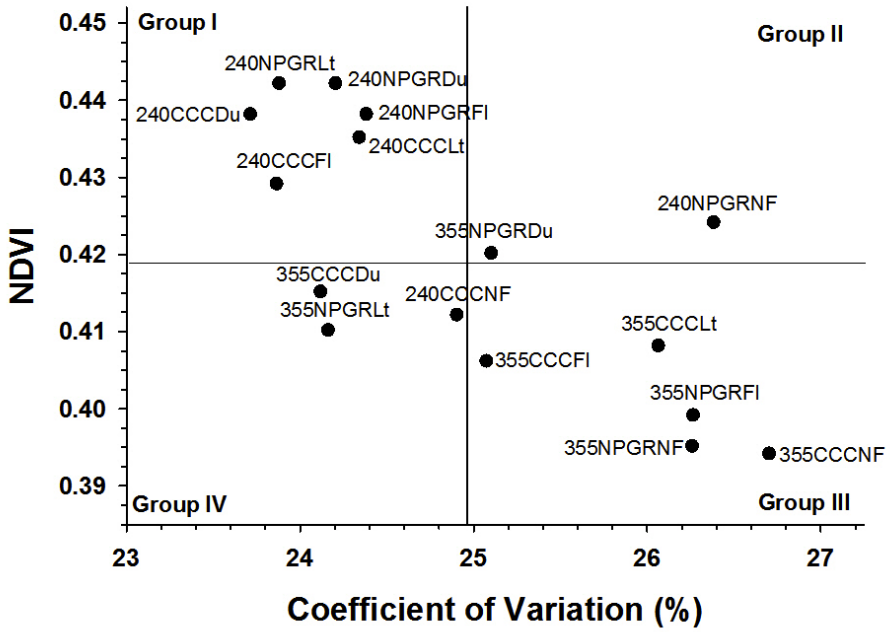

Figure 3-3. Biplot summarizing SRxPGRxFung means vs. CV for NDVI across 14 Alberta environments. Grouping categories: Group I: high mean, low variability; Group II: high mean, high variability; Group III: low mean, high variability; Group IV: low mean, low variability. Treatment legend: 240: 240 plants m^{-2} target seeding rate; 355: 355 plants m^{-2} target seeding rate; NPGR: control plant growth regulator; CCC: chlormequat chloride; NF: control fungicide; Fl: flag fungicide timing; Lt: late fungicide timing; Du: dual fungicide application.

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Chapter Four: Effect of post-emergence N application and the urease inhibitor NBPT on feed barley production in Alberta.

4.1. Introduction

Alberta produces the majority of feed barley in Western Canada to supply feed grain to a cattle industry of 4.8 million animals (Statistics Canada, 2016a). Barley in the western Canadian crop rotation also increases crop diversity, which is favourable in the current high frequency canola rotation (1 in 2 years) that represented nearly half of 223 surveyed fields in Alberta between 2007-2010 (personal communication, Julia Leeson, 2017). Increased crop diversity results in higher yields or lessened requirements for pesticide use in the system because of lower disease and insect outbreak risk (Harker et al., 2014; O'Donovan et al., 2014; Turkington et al., 2012). However, seeded barley acres in Alberta declined by an average of 3.4% $year^{-1}$ between 2006 and 2016 (Statistics Canada, 2016b). Furthermore, between 1991 to 2016, Alberta on-farm barley yields have increased by an average of 30.8 kg ha^{-1} $year^{-1}$ (1.1%) while on-farm Canada western red spring wheat yields have increased at a greater pace by an average of 52 kg ha^{-1} $year^{-1}$ (2.7%) (Statistics Canada, 2017). Genetic yield advances do not appear to present an immediate solution to increase feed barley yields provincially because both on-farm and small-plot yield data suggest the grain yields of recently registered feed barley cultivars have not improved in relation to cultivars registered 10 to 15 years prior (Figure 4.1) (Agriculture Financial Services Corporation, 2016; Alberta Agriculture and Forestry, 2016a). Although biases such as cultivar acreage and management practices exist in on-

farm data, this suggests that an agronomic solution is required to assist in improving feed barley yields. In order for barley to remain an economically viable crop choice for producers, high grain yields are required to balance the low commodity prices of feed barley. The current feed barley production practice in Alberta consists of 100% of N requirements met at the time of seeding, but additional post-emergence nitrogen (N) at the time of maximum N uptake may provide a solution to increase yields.

Barley N needs have been historically met at seeding time in western Canada and the positive barley yield response to increasing N rate at seeding has been established (McKenzie et al., 2004b; O'Donovan et al., 2011; O'Donovan et al., 2015). However, additional applications of N after crop emergence have been the subject of limited research. In a study from Uruguay, N application at BBCH 30 (Lancashire et al., 1991) increased spring barley grain yields only if there was adequate N applied at seeding to support early season growth in high precipitation Uruguay production environments (Baethgen et al., 1995). Post-emergence N application just prior to BBCH 30, the time of maximum crop uptake (Baethgen and Alley, 1989; López-Bellido et al., 2005; Mossedaq and Smith, 1994), may increase grain yield. The feed barley yield, agronomic, and quality responses to additional N applied just prior to BBCH 30 have not been determined in the unique edaphic and climatic conditions of Alberta.

Lodging is a major feed barley production constraint that is exacerbated by high rates of N fertilizer (Berry et al., 2000; Caldwell, 1983; Rajkumara, 2008). Increasing N rate at seeding resulted in increased lodging of malt barley cultivars in Western Canada (O'Donovan et al., 2011; O'Donovan et al., 2015). Lodging yield losses result from

reduced photosynthetic capacity and from reduced photosynthate translocation (Berry and Spink, 2012), which is why the most severe yield losses, between to 13 and 40 % in Alberta, occurred when lodging took place during the grain filling period (Jedel and Helm, 1991). In addition to reduced yields, the risk of reduced grain quality due to fungal infection of the grain increases when lodging occurs (Berry et al., 2004).

Extended maturity in the short frost-free Alberta growing season can lead to reduced grain yield and quality caused by frost damage. Increasing rates of N between 0 and 120 kg ha^{-1}, applied at seeding, increased maturity by 2-3 days in western Canadian environments (O'Donovan et al., 2011; O'Donovan et al., 2015). The effect of post-emergence N on feed barley maturity must be considered because of the production consequences of lengthened maturity in the short western Canadian growing season.

Test weight is an important parameter used to determine feed barley quality. Feed barley test weight must be above 59 kg hL^{-1} to meet the Canada No. 1 Grade, and test weights below this threshold are subject to price discounts (Grimson et al., 1987). Higher test weight barley had increased digestibility in feedlot cattle because of lower fiber content (Yang et al., 2013). For equivalent weight gain in feedlot steers, 1.2% more dry matter was required for each 1 kg hL^{-1} decrease in barley test weight between 56 to 48 kg hL^{-1} (Grimson et al., 1987). Additionally, high test weight barley increases equipment handling capacity and requires less processing in feedlots (Mathison, 2000). A negative relationship between N rate applied at seeding and feed barley test weight was reported in southern Alberta (McKenzie et al., 2004b).

In addition to test weight, grain starch and fiber content are important feed barley quality parameters. Grain starch and fiber concentration are negatively correlated, with starch being highly digestible and positively related to the energy required for feedlot cattle weight gain (Surber et al., 2000). Acid detergent fiber (ADF) is composed of the less digestible cell wall components cellulose and lignin, and it is a sub-fraction of neutral detergent fiber (NDF) that is composed of the cell wall components cellulose, lignin, and hemi-cellulose. Barley grain with high ADF or NDF concentrations and low starch concentration had reduced digestibility in feedlot cattle and often had reduced feed efficiency (Engstrom et al., 1992; Ovenell-Roy et al., 1998b). Surbur et al. (2000) suggested selecting feed barley with high starch and low ADF concentration to increase feed barley quality. Limited information is available on the effect of post-emergence N on barley grain starch and fiber composition. In Sweden, grain yield and kernel number spike^{-1} increased while grain starch concentration decreased by 4% with increasing N rate applied at seeding between 45 and 135 kg ha^{-1} (Oscarsson et al., 1998).

Volatilization N loss of ammonia (NH_3) gas occurs when urea is hydrolyzed by the soil microbial urease enzyme into unstable carbamic acid (H_2NCOOH), which then decomposes into NH_3 that is lost to the atmosphere (Terman, 1979). Soil conditions that favour volatilization include low cation exchange capacity (CEC), low organic matter content, high pH, and coarse texture (Rawluk, 2000; Watson et al., 1994). Environmental factors that encourage volatilization loss include low soil moisture, soil water flux resulting from small rainfall events following fertilizer application, and high soil temperature (Rawluk, 2000). Surface applied N fertilizers are at higher risk of

volatilization N loss than sub-surface applied fertilizers. Urease inhibitors can be added to surface applied, post-emergence UAN applications to reduce volatilization loss by inhibiting urease activity and delaying urea hydrolysis to NH_4^+. Urease inhibitors such as (*N*-(n-butyl) thiophosphoric triamide) (NBPT) are effective at reducing volatilization N loss when conditions favour volatilization (Fenn and Hossner, 1985; Watson et al., 1994).

The objectives of this study were: i) to determine the effect of increasing rates of post-emergence N on feed barley grain yield, agronomic responses, and grain quality; ii) to determine the effect of the urease inhibitor NBPT on grain yield, agronomic responses, and grain quality; iii) to determine the effect of environment on grain yield, agronomic, and grain quality responses to post emergence N.

4.2. Materials and Methods

Field experiments were conducted over three growing seasons from 2014-2016 at four rain-fed sites and one irrigated site in the major agro-climatic zones of Alberta, Canada, under no-tillage management (Table 4.1). Soil was sampled prior to seeding (Table 4.2). Growing season precipitation was acquired from the nearest weather station (Table 4.1).

The cultivar selected for the study was Amisk (Nyachiro, 2013), a six-row feed cultivar with intermediate resistance to scald (*Rhynchosporium commune* Zaffarano, McDonald and Linde sp. nov. (formerly known as *Rhynchosporium secalis* (Oudem.) J. J. Davis) and net form net blotch (*Drechslera teres* (Sacc.) Shoemaker), moderate resistance to spot form net blotch (*Drechslera teres f. maculata* Smedeg.), and very good lodging

resistance (Alberta Agriculture and Forestry, 2016a). Amisk was selected in the study because it represented new feed barley genetics and was promoted as a high yielding, high quality cultivar. Seeding rate was calculated using thousand-kernel weight, germination percentage, and predicted emergence mortality (10%) to achieve plant stand densities of 240 or 355 plants m^{-2}. Seed was treated with difenoconazole {1-(2-[4-(chlorophenoxy)-2-chlorophenyl-(4-methyl-1,3-dioxolan-2-yl)-methyl])-1H-1,2,4-triazole}, metalaxyl [N-(2,6-dimethylphenyl)-N-(methoxyacetyl)-alanine methyl ester], and sedaxane (N-[2-[1,1'-bicyclopropyl]-2-ylphenyl]-3-(difluoromethyl)-1-methyl-1H-pyrazole-4-carboxamide) formulated as Vibrance XL (Syngenta Canada Inc.). Opener type, fertilizer placement, row spacing, and seeded plot size varied between location and years (Table 4.3). Appropriate seeding fertilizer rates were based on soil test results (Table 4.2) for yield targets based on the land co-operator 10-year feed barley yield average (Table 4.4). Nitrogen, P, K, and S were applied at seeding as granular fertilizer in the form of urea (46-0-0-0), mono-ammonium phosphate (11-52-0-0), potassium (0-0-60-0), and ammonium sulfate (21-0-0-24) (Table 4). Seed safe levels of P were applied in the seed row (22 kg ha^{-1} at Falher, Bon Accord, and Killam; 45kg ha^{-1} at Lethbridge rainfed, and 30kg ha^{-1} at Lethbridge irrigated) and the remaining, if required, was side banded or mid-row banded with the N, K, and S fertilizer. Pre-emergence and in-crop herbicides were applied using TeeJet TT11002 nozzles as required for weed control (Table 4.5). Insecticide was applied to trial areas as required to control insect pests (Table 4.6). Seeding and harvest date varied between site and year (Table 4.1). All treatments were direct seeded at a depth to reach soil moisture (2.5 to 3.8cm seeding depth) into canola (*Brassica napus* L.) stubble.

Glyphosate (N-(phosphonomethyl)glycine) was applied pre-harvest at 360 g ae ha^{-1} rate when grain moisture content was < 30% to assist with harvest management.

The experimental design was a strip-plot design with four levels of post-emergence N rate comprising the horizontal strip and combinations of seeding rate, the plant growth regulator (PGR) chlormequat chloride, and foliar fungicide as the vertical strip with 16 levels (SRxPGRxFung). Horizontal strip layout within the trial is indicated in Appendix Figure 1. Detailed description of the vertical strip treatment combinations, product rates, and application times are found in Chapter 3. Post-emergence N was surface banded as undiluted urea-ammonium nitrate (UAN) (28% N) with Teejet StreamJet SJ3-015 nozzles just prior to BBCH 30 (Lancashire et al., 1991) at four levels: 0, 34, and 64 kg N ha^{-1}, and 34 kg N ha^{-1} with the urease inhibitor N-(n-butyl) thiophosphoric triamide (NPBT) formulated as Agrotain (Koch Agronomic Services, LLC, Wichita, KS) at a rate of 476 ml ha^{-1}. Post-emergence N calendar application date varied between site-years (Table 4.8). A fungicide application rate error occurred at Killam 2015 and treatment results from this site-year were excluded from data analysis.

Barley stand density was determined 2 weeks after emergence by counting plants in two 1-m row lengths in each plot. If visual leaf burn was present following UAN application, normalized difference vegetation index (NDVI) measurements were taken using a handheld GreenSeeker (Trimble Navigation Ltd, Sunnyvale, CA) on 8 plots (control CCC) in the 2nd and 3rd replicates two and ten days after UAN application to help quantify visual leaf burn between post-emergence N treatments. Plant height was quantified after BBCH 83 by measuring the height of 4 main tillers from the inner plot rows from the

ground to the top of the spike (excluding awns). Main stem spike length was determined at the same time by measuring the distance to the spike base and subtracting it from the distance to the top of the spike, excluding awns. To quantify crop greenness differences between post-emergence N treatments, NDVI was measured in all plots between BBCH 83 and 85. Five flag and 5 penultimate leaf samples were collected from the inner rows of each plot from all treatments in one replicate 7-10 days after the 2^{nd} fungicide application. Ten main stem heads from each plot were collected at 30 to 40% grain moisture and days to maturity were determined according to Karamanos et al. (2008). Lodging index (Berry et al., 2003) was measured at physiological maturity. Grain was harvested using Wintersteiger Delta small plot combines (Wintersteiger Inc., Saskatoon, Canada) with 2012 classic grain gauge automatic weigh systems at physiological maturity. Yield, yield component, and quality data were adjusted to the Canadian Grain Commission standard of 14.8% grain moisture. Test weight was either automatically determined by the combine weigh system or measured using a GAC 2100 Dickey-john grain moisture tester (Churchill Industries, Minneapolis, MN). Kernel weight (g thousand-kernels^{-1}) was determined by weighing 500 kernels and multiplying the resulting weight by 2. Grain protein, starch, ADF, and NDF concentrations were determined with a DS2500 near infrared reflectance (NIR) spectrometer (FOSS, Eden Prairie, MN 55344, USA). Nitrogen yield was determined by multiplying grain yield x percent nitrogen in the grain, as determined by NIR analysis. Due to various logistical constraints, not every category of data was collected at each site-year.

Data were analyzed using PROC MIXED of SAS version 9.4 (SAS Institute Inc., 2014). Lodging data was transformed using the log10 data transformation to achieve normality, and least significant means were reported as the back transformed values. Post-emergence N (horizontal strip) and SRxPGRxFung combinations (vertical strip) were considered fixed effects. The layout of the horizontally oriented plots (horizontal strips) within the trial is indicated in Appendix Figure 1. Location by year combinations (14 site-years), replicates within site-years, and site-year interactions with fixed effects were considered random. Exploratory analyses revealed that residual variances were heterogeneous among environments. Variance heterogeneity was modeled for all analyses using a repeated statement for PROC MIXED with the group option set to site-year. Future performance of treatments at untested locations may be inferred by considering site-year and the interactions between site-year and the treatments (fixed effects) as random, and the large number of site years analyzed (14) facilitated this approach (Yang, 2010). Orthogonal contrast statements were used to test for linear and quadratic responses to post-emergence N at an $\alpha < 0.05$.

Environment (site-year) interactions with treatments were assessed using the Wald Z test to determine if variance estimates were different than zero at an α level of 0.01. The relative size of the variance estimate for the environment by post-emergence N interactions compared with the sum of the variance estimates for all effects including environment was also used to determine the importance of the random environment by treatment interactions (Piepho, 2017). Environment x post-emergence N (ExN) interactions were considered large if the relative size of the variance estimate for the ExN

interaction compared with the sum of the variance estimates for all effects including environment was larger than 10%.

When the ExN variance estimates were relatively large or significant, a grouping methodology, as previously described by Francis and Kannenberg (1978), was used to explore treatment responses and variability. The mean and coefficient of variation (CV) were estimated for treatments across years and replicates. Means were plotted against CV for response variables that had a large or significant ExN variance estimate, and the overall mean of means and CVs was included in the plot to categorize the data into four categories: Group I: High mean, low variability; Group II: High mean, high variability; Group III: Low mean, high variability; and Group IV: Low mean, low variability.

4.3. Results and Discussion

Interactions did not occur between post-emergence N and SRxPGRxFung combinations for any variable with the exception of grain NDF concentration (Chapter 3). Detailed explanation surrounding the absence and occurrence of interactions between post-emergence N and SRxPGRxFung combinations can be found in Chapter 3. Post-emergence N treatment means were presented across SRxPGRxFung combinations for all variables (Table 4.8).

4.3.1 Environmental conditions

Growing season rainfall varied considerably across the 14 environments where trials were conducted (Table 4.1). Precipitation was above the growing season long-term

normal (inclusive of irrigation) in 9 environments (326mm to 502mm) and below the growing season long-term normal in 5 environments (101mm to 323mm). As expected, the environment had a large (>10) or significant ($p<0.01$) effect on most variables (Table 4.7). High precipitation environments tended to have taller plants, longer maturity, and higher grain yield, test weight, starch concentration, and grain N yield, but lower protein concentration compared to environments with below average growing season precipitation (data not shown). Of greater importance was the significance and size of the environment x post-emergence N interactions (Table 4.7). The environment x post-emergence N interaction was small (<8) for every variable, but it was significant ($p<0.01$) for NDVI, grain yield, grain N yield, and grain protein, indicating that environment influenced these responses to post-emergence N application (Table 4.7).

4.3.2. Effect of increasing post-emergence N rate

Post-emergence N affected plant height, NDVI, maturity, grain yield, grain N yield, grain protein concentration, and grain starch while there were no significant effects on spike length, lodging, kernel weight, test weight, ADF, and NDF (Table 4.7).

A linear height increase occurred with increasing post-emergence N rate; however, the height increase did not result in increased lodging (Table 4.7). In Uruguay, lodging occurred when greater than 30 kg N ha^{-1} was applied at BBCH 22 but not at BBCH 30 (Baethgen et al., 1995). In western Canada, O'Donovan et al. (2015) reported malt barley cultivars with genetic resistance to lodging had less lodging at higher N rates applied at seeding compared to cultivars lacking genetic resistance to lodging. The

genetic lodging resistance of cv. Amisk (Alberta Agriculture and Forestry, 2016a) may have negated the anticipated lodging response to increasing rates of post-emergence N at BBCH 30. Alternately, post-emergence N applied just prior to BBCH 30 may have a smaller effect on lodging than N applied at seeding.

Maturity increased with increasing post-emergence N rate by less than 1 day (Table 4.8). Similarly small magnitude increases in maturity were reported in response to increasing N rates between 0 and 60 kg ha^{-1} applied at seeding (O'Donovan et al., 2011; O'Donovan et al., 2015). The small maturity increase resulting from post-emergence N application did not present production risks because maturity in this study ranged from 98.1 to 98.9 days, which was within the historical frost-free period of 115 to 125 days in all study environments (data not shown) (Alberta Agriculture and Forestry, 2016b).

NDVI measured at BBCH 83-85 increased linearly with increasing post-emergence N rate (Table 4.7). The increase in NDVI may have been an indication of leaf N status. Leaf chlorophyll content increased with increasing N rate applied at seeding in western Canadian barley production (O'Donovan et al., 2015). Alternatively, NDVI increases may have been associated with the lengthened maturity at increasing post-emergence N rate (Table 4.8). Importantly, the effect of post-emergence N rate on NDVI depended on environment, as indicated by the significant environment x post-emergence N interaction for NDVI (Table 4.7). Biplot analysis comparing mean and coefficient of variation (CV) of NDVI treatments across environments revealed lower variability for the 34 and 68 kg ha^{-1} post-emergence N rates compared to the 0 kg ha^{-1} post-emergence N rate (Figure 2a), meaning that post-emergence N resulted in more consistently green plants across

environments. Individual site-year analysis revealed that NDVI increased with increasing N rate in most environments except for Bon Accord 2015 where NDVI was highest for the 0 kg ha^{-1} post-emergence N rate (data not shown). The higher NDVI for the 0 kg ha^{-1} post-emergence N treatment in the Bon Accord 2015 environment was caused by early season UAN leaf damage sustained on the 34 and 68 kg ha^{-1} N treatments during UAN application in high temperatures (Table 4.12). However, similar to other environments, NDVI for the 68 kg ha^{-1} post-emergence N rate was greater than the 34 kg ha^{-1} post-emergence N rate at Bon Accord 2015 (data not shown), providing an explanation for the increased variability of the 0 kg ha^{-1} rate but not of the 34 and 68 kg ha^{-1} post-emergence N rates. Contact of concentrated fertilizers with the leaf surface can result in leaf burn in high temperature conditions (Fageria et al., 2009). There was also limited growing season precipitation Bon Accord 2015 that contributed to stressful growing conditions during UAN application (Table 4.1). NDVI measurements recorded 2 and 10 days after UAN application at Bon Accord 2015 showed decreasing NDVI with increasing post-emergence N rate, indicative of leaf burn (Table 4.10). Some plant recovery likely occurred after UAN application during the growing season at Bon Accord 2015, which resulted in higher NDVI for the 68 kg ha^{-1} treatment compared to the 34 kg ha^{-1} post-emergence N treatment at BBCH 83 (data not shown), the time of NDVI measurement.

Post-emergence N did not increase spike length (Table 4.7). Baethgen et al. (1995) reported barley kernels $spike^{-1}$ increased between 30 and 100% with N application at BBCH 30 compared to treatments without fertilizer in high precipitation environments. It was expected that spike length may have increased due to a greater number of kernels

on the spike. The higher initial rates of N fertilizer applied at seeding in the present study may have negated spike length increase. Additionally, the compact spike morphology of the six-row cv. Amisk may have prevented detectible increases in spike length resulting from small increases in kernels spike^{-1} in the present study.

Grain yield increased linearly with increasing post emergence N rate (Table 4.7). The grain yield increase may be partly attributed to increased photosynthetic capacity, as supported by the increase in NDVI with increasing post-emergence N rate (Table 4.7). However, grain yield response to post-emergence N varied across environments as indicated by the significant environment x N interaction for grain yield (Table 4.7). Biplot analysis comparing mean grain yield to the grain yield coefficient of variation (CV) revealed increased variability for post-emergence N treatments, particularly 68 kg N ha^{-1}, compared to the 0 kg ha^{-1} N control (Figure 2b). Individual site-year analysis showed there were grain yield increases in response to post-emergence N in 10 environments (Bon Accord 2014, Bon Accord 2016, Falher 2016, Killam 2016, and at Lethbridge Irrigated and Rainfed in all 3 years), there was no grain yield change in 3 environments (Falher 2014 and 2015, and Killam 2014), and there was reduced grain yield in 1 environment (Bon Accord 2015) (data not shown). The 10 environments where grain yield increases occurred generally had near or above the long-term average growing season precipitation (Table 4.1). Baethgen et al (1995) also reported N application at BBCH 30 resulted in barley grain yield increases in the high moisture conditions of Uruguay environments (>500mm in the growing season). The largest yield increases occurred in the Lethbridge Rainfed and Irrigated locations in 2014, 2015, and 2016, and

ranged between 4 and 10% (for the 34 kg N ha^{-1}) and 5 and 19% (for the 68 kg N ha^{-1}) compared to the 0 kg N ha^{-1} control. The Lethbridge Rainfed and Irrigated sites in 2015 and 2016 received lower amounts of N at seeding relative to other environments (Table 4.4) and this may have contributed to the larger grain yield responses to post-emergence N. Opposite to these increases, grain yield at Bon Accord in 2015 decreased by 9 and 13% compared to the control at the 34 and the 68 kg ha^{-1} post-emergence N rates, respectively (data not shown). Conditions favourable for plant stress (low relative humidity coupled with high air temperatures) occurred on the day of post-emergence N application (Table 4.9). As previously discussed, visible leaf burn in the 34 and 68 kg N ha^{-1} treatments corresponded to reduced NDVI by 4-6% compared to the control two days after UAN fertilizer application and by 4-5% compared to control ten days after application at Bon Accord 2015 (Table 4.10). High temperatures and mid to low relative humidity during UAN application likely caused the grain yield and NDVI reductions associated with post-emergence N application at Bon Accord 2015. Addition of NBPT did not reduce the grain yield decrease observed at Bon Accord 2015 from post-emergence N application (data not shown).

Post-emergence N did not affect test weight (Table 4.7). In contrast, McKenzie et al. (2004b) reported increasing N rate at seeding reduced barley test weight, an important quality parameter for feed barley. Our results indicate that although post-emergence N application did not improve feed barley test weight, it also did not result in reduced feed quality from lower test weight.

Kernel weight was also unaffected by post emergence N (Table 4.7). Therefore, kernel weight did not contribute to the grain yield increase that resulted from post-emergence N application. This result agreed with the limited barley kernel weight response to post-emergence N at BBCH 30 reported in high precipitation (>500mm in the growing season) conditions in Uruguay (Baethgen et al., 1995), but it was contrasted by the kernel weight increase reported with increasing N applied at seeding in western Canada (O'Donovan et al., 2011). The grain yield increase from post-emergence N was likely caused by increased photosynthetic capacity in combination with increases in unmeasured yield components such as kernels spike^{-1}, spikes m^{-2} (tillers plant^{-1}), or kernels m^{-2} as reported with post-emergence N applied under high precipitation conditions (Baethgen et al., 1995) and with increasing N rates applied at seeding (O'Donovan et al., 2015).

Grain protein increased linearly with increasing rates of post-emergence N (Table 4.7). Western Canadian studies have similarly reported linear barley grain protein increases with increasing rate of N applied at seeding (McKenzie et al., 2004b; O'Donovan et al., 2011; 2015). Although protein increase is unfavourable for malt barley quality (BMBRI, 2012), higher protein levels improve feed barley quality particularly for monogastric livestock. The 4 and 6% protein increases of the 34 and 68 kg ha^{-1} post-emergence N treatments, respectively, relative to the 0 kg ha^{-1} post-emergence N control (Table 4.8) were comparable to the 0 to 5% protein increases reported by Bulman et al. (1993) in response to 50 kg ha^{-1} N applied post-anthesis, preceded by 100 kg ha^{-1} N applied at seeding in eastern Canada. This suggests that N application just prior to BBCH

30 resulted in comparable magnitude increases in barley grain protein to N applications made post-anthesis.

Importantly, the protein response to post-emergence N varied between environments (Table 4.7). Individual site-year analysis revealed N rate applied at seeding (Table 4.4) appeared to have a greater influence on protein response than growing season precipitation (Table 4.1) and environments that received larger amounts of N at seeding had smaller grain protein responses to post-emergence N application compared to environments with relatively smaller amounts of N applied at seeding (data not shown). For example, below average growing season precipitation environments (Lethbridge rainfed 2015 and 2016) and above average growing season precipitation environments (Lethbridge irrigated 2015 and 2016) that had relatively low rates of N applied at seeding (Table 4.4) had protein increases ranging between 3 and 7% (34 kg ha^{-1} post-emergence N) and between 7 and 13% (68 kg ha^{-1} post-emergence N) (data not shown). Conversely, Lethbridge irrigated 2014 and Killam 2016 had above average growing season precipitation and relatively high rates of N applied at seeding, and there was no significant effect of post-emergence N on grain protein (data not shown). Similarly, the dry environment at Falher 2014 had more N applied at seeding than the below and above average precipitation environments at Falher 2015 and 2016, respectively, but Falher 2014 had smaller protein increases (1 to 2%) in response to post emergence N compared to the larger responses (4 to 7%) at Falher 2015 and Falher 2016 (data not shown). This suggests that when lower N rates are applied at seeding, post-emergent N applications can result in larger protein increases. In eastern Canada, protein

increases were similarly small or not significant when high (100kg ha^{-1}) amounts of N at seeding accompanied 50 kg ha^{-1} post-emergence N applied post-anthesis (Bulman and Smith, 1993).

The biplot analysis indicated higher grain protein stability occurred with increasing rates of post-emergence N (Figure 2c). The higher protein stability of the post-emergence N treatments was likely a result of protein increases and the absence of protein decreases in environments (data not shown). Additionally, the sole N source for the 0 kg ha^{-1} post-emergence N treatment (N applied at seeding, soil nitrate, and organic matter) was exposed to environmental influences and possible N losses prior to uptake for a longer period of time compared to the N applied just prior to BBCH 30 in the 34 and 68kg ha^{-1} post-emergence N treatments, and this may have contributed to the increased protein variability of the 0 kg ha^{-1} post-emergence N treatment. Although moisture limited environments had higher grain protein concentrations (data not shown) as supported by other western Canadian reports (Grant et al., 1991a), our results suggest that grain protein increases in response to post-emergence N were not magnified under low moisture conditions, rather, the amount of N applied at seeding influenced the magnitude response to post-emergence N rate.

Grain N yield increased linearly with increasing post-emergence N rate similar to the yield and protein responses to post-emergence N rate (Table 4.7). This result agrees with McKenzie et al. (2004b) who reported that grain N yield increases resulting from increasing N rates applied at seeding were correlated to grain yield increases in central Alberta. In the present study, not all post-emergence N applied was recovered in the

grain, with the 34 and 68kg N ha^{-1} post emergence N treatments increasing grain N yield by 8 kg N ha^{-1} (6%) and 11 kg N ha^{-1} (9%), respectively (Table 4.8). Importantly, the response to post-emergence N depended on the environment (Table 4.7) and biplot analysis comparing mean grain N yield to the grain N yield coefficient of variation (CV) revealed increased variability for post-emergence N treatments compared to the 0 kg ha^{-1} N control (Figure 4.2d). Individual site-year analysis revealed the effect of environment on N yield followed the effects of environment on grain yield and protein. Environments with high precipitation (Table 4.1) or relatively less N applied at seeding (Table 4.4) had larger grain N yield increases in response to increasing rate of post-emergence N compared to environments with less precipitation or more N applied at seeding (data not shown). For example, Falher 2014 had the lowest growing season precipitation in the study, and there was no significant N yield increase in response to post-emergence N (data not shown). In agreement with this result, Grant et al. (1991a) also reported that N uptake decreased with decreasing moisture conditions in Manitoba environments. The Lethbridge rainfed environments in 2015 and 2016 had relatively low amounts of N applied at seeding and also had relatively large grain N yield increases, between 10 and 14% for the 34 kg N ha^{-1} post emergence N treatment and between 21 and 22% for the 68 kg N ha^{-1} post emergence N treatment compared to the control (data not shown). It is notable that at the Lethbridge rainfed site in 2015, growing season precipitation was less than half of the average (Table 4.1), and grain N yield increases were relatively large at 10 and 21% for the 34 and 68 kg ha^{-1} N treatments, respectively, compared to the control (data not shown). This suggests N yield increases can still occur in dry environments if N

applied at seeding is low. Killam 2014 and 2016 environments had relatively high amounts of N applied at seeding (Table 4.4), and the grain N yield increases were relatively small, ranging between 4 and 7% for all post-emergence N treatments (data not shown). At Bon Accord 2015 where precipitation was below average (Table 4.1) and where post-emergence N application occurred in hot and dry conditions (Table 4.9), the 34 and 68 kg ha^{-1} N treatments significantly decreased grain N yield 5% and 7%, respectively, similar to the effect of post-emergence N on grain yield in this environment (data not shown). These results suggest that both growing season precipitation and N applied at seeding are important factors influencing grain N yield response to post-emergence N application.

Grain starch concentration decreased by less than 1% with increasing post-emergence N rate compared to the 0 kg ha^{-1} post emergence N control (Table 4.8). Oscarsson et al. (1998) reported a 4% decrease in barley grain starch concentration in Sweden with increasing rate of N applied at seeding (45 to 135 kg ha^{-1}). The grain starch decrease reported by Oscarsson et al. (1998) was attributed to dilution of starch concentration caused by corresponding increases in grain yield and kernel number with increasing N rate, which may also be the case in our study. In the present study, the small decreases in grain starch concentration were statistically but not agronomically or biologically significant, and therefore post-emergence N did not negatively affect feed quality.

4.3.3. Effect of NBPT

The addition of the urease inhibitor NPBT to the 34 kg N ha^{-1} treatment did not significantly affect any variables when compared to the 0, 34, and 68 kg N ha^{-1} rates without NBPT (Table 4.7). Grant (2013) also reported no grain yield difference in hard red spring wheat yield between surface banded UAN with or without NBPT applied at seeding time in Manitoba environments. However, the ANOVA revealed significant environment x post emergence N interactions for NDVI, grain yield, N yield, and protein, indicating that these responses to post-emergence N treatments varied across environments (Table 4.7). Biplot analysis indicated larger variability of the NBPT amended post-emergence N treatment for NDVI and grain yield (Figure 4.2a, 4.2b), similar variability for protein (Figure 4.2c), and less variability for N yield (Figure 4.2d).

Opposite to the overall NS effect of 34 kg ha^{-1} post-emergence N + NBPT on NDVI observed in the study (Table 4.7), individual site year analysis revealed that small NDVI decreases between 1 and 4% occurred in 4 environments (Bon Accord 2014, Killam 2016, Lethbridge Rainfed 2015, and Lethbridge Irrigated 2015) with 34 kg N ha^{-1} + NBPT compared to the 0, 34, and 68 kg N ha^{-1} rates (data not shown). These occasional NDVI decreases likely contributed to the increased variability observed for the NBPT treatment compared to the unamended post-emergence N treatments in the biplot analysis (Figure 4.2a). Although unexpected, the NDVI reductions were small and they did not translate into reductions in grain yield, protein, or N yield.

Falher 2014 was the only environment where the 34 kg N ha^{-1} + NBPT treatment increased grain yield and N yield compared to the 0, 34, and 68 kg N ha^{-1} post-emergence

N treatments (data not shown). The 5% yield and 4% N yield increases at Falher 2014 were likely related to greater reduction of ammonia (NH_3) volatilization for the NBPT amended treatment where soil and environmental conditions were conducive to N volatilization. These conditions were: low soil CEC and soil organic matter (Table 4.2), extremely low moisture (101mm growing season precipitation) and low relative humidity that were indicative of the dry soil conditions surrounding UAN application, and frequent small rainfall events following UAN application (Table 4.9). The reduced ammonia loss from NBPT amended UAN, compared to unamended UAN, was greater for non-irrigated (lower moisture) soils compared to irrigated (high moisture) soils in Manitoba (Rawluk, 2000). Wetting and drying of the soil resulting from small rainfall events encourages N loss by concentrating NH_4^+ near the soil surface and driving the equilibrium between NH_4^+ and NH_3 in the soil solution towards $NH_{3(gas)}$. Lethbridge rainfed 2014 had similarly frequent small rainfall events as Falher 2014 (Table 4.9); however, the growing season precipitation at Lethbridge rainfed 2014 was above average (Table 4.1), which indicates greater soil moisture. Initial soil moisture influences the amount of N volatilization loss resulting from small rainfall events, with dry soils suffering greater loss from small rainfall events than initially higher moisture soils (Rawluk, 2000). The low amount of precipitation observed during the growing season (Table 4.1) and the low relative humidity (Table 4.12) at Falher 2014 indicate dry soil conditions, and the frequent small rainfall events following post-emergence N application (Table 4.2) likely resulted in greater N loss through volatilization compared to other sites. The reduction of NH_3 volatilization losses from surface applied urea treated with NBPT was greater in soils with

lower CEC (Watson et al., 1994). The soil CEC and soil organic matter at Falher 2014 were among the lowest of all 14 environments (Table 4.2). High pH soils also favour ammonia volatilization (San Francisco et al., 2011; Watson et al., 1994), but environments with high pH soils did not favour increased yields with NBPT amended UAN in the present study, as may have been expected. It was notable that yield response to NBPT was not consistently a function of soil CEC or soil pH across environments, to the number of small rainfall events following post-emergence N application, or to periods without rainfall following post-emergence N application (Table 4.12) (data not shown), likely due to the multiple environmental factors that influence NH_3 volatilization including initial soil moisture, soil water flux, and soil temperature, and urease activity (Rawluk, 2000). Our study indicates that NBPT with surface banded post-emergence N just prior to BBCH 30 resulted in infrequent grain yield and N yield increases compared to unamended post-emergence N in only one of 14 environments. The positive response to NBPT was observed in an environment that had low soil CEC, dry growing conditions, and frequent small rainfall events following UAN application.

4.4. Conclusion

Application of post-emergence N just prior to BBCH 30 resulted in linear grain yield increases of up to 19%, and also resulted in linear grain N yield increases of up to 22% when growing season precipitation was adequate or above normal and when lower rates of baseline N were applied at seeding. Yield decreases up to 13% and N yield decreases of up to 7% occurred when post-emergence N was applied under high

temperature and low soil moisture conditions, and this negative result was not eliminated by the addition of NBPT. Application of UAN to plants in high temperature and low relative humidity conditions should be avoided. In-season agronomic decision-making based on precipitation level and current environmental conditions is required for optimal yield response to post-emergence N.

Post-emergence N application did not adversely impact important agronomic factors such as maturity and lodging. No marked improvement of feed barley quality as measured by test weight, grain starch, ADF, and NDF concentrations occurred. However, lower rates of N applied at seeding resulted in larger protein increases in response to post-emergence N.

The urease inhibitor NBPT increased feed barley grain yield and N yield responses to post-emergence N at 1 of 14 site years, where soil organic matter and CEC were low, and had no effect on other variables in the diverse edaphic environments of the study.

Post-emergence N application increased feed barley grain yields up to 19% in environments with adequate growing season precipitation or with less N applied at seeding, without negative agronomic or quality impact. In-season decisions based on precipitation amount and temperature are required to maximize yield response to post-emergence N.

Table 4-1. Soil classification, seeding date, harvest date, growing season precipitation, and site coordinates for each environment (site-year).

Location	Year	Coordinates	Great Group classification	Canadian equivalent	Seeding date	Harvest date	Observed precipitation†	Long-term mean precipitation‡
							mm	
Bon Accord	2014	53°48'N 113°28'W	Udic Boroll	Black Chernozem	9 May	4 Sept	181	344
Rainfed	2015	53°48'N 113°27'W	Udic Boroll	Black Chernozem	27 April	31 Aug	121	
	2016	53°55'N 113°27'W	Udic Boroll	Black Chernozem	28 April	8 Sept	323	
Falher	2014	55°48'N 117°11'W	Boraf	Gray Luvisol	22 May	30 Aug	101	301
Rainfed	2015	55°47'N 117°10'W	Boraf	Gray Luvisol	14 May	3 Sept	155	
	2016	55°40'N 117°2' W	Boraf	Gray Luvisol	10 May	15 Sept	338	
Killam	2014	52°48'N 111°52'W	Udic Boroll	Black Chernozem	24 May	25 Aug	263	309
Rainfed	2016	52°51'N 111°53'W	Udic Boroll	Black Chernozem	16 May	14 Sept	345	
Lethbridge	2014	49°22'N 112°55'W	Typic Boroll	Dark Brown Chernozem	1 May	16 Sept	426	317
Irrigated	2015	49°41'N 112°39'W	Typic Boroll	Dark Brown Chernozem	24 April	12 Aug	282	
	2016	49°42'N 112°31'W	Typic Boroll	Dark Brown Chernozem	11 April	17 Aug	502	
Lethbridge	2014	50°33'N 113°53'W	Udic Boroll	Black Chernozem	16 May	17 Sept	326	305
Rainfed	2015	49°22'N 112°55'W	Typic Boroll	Dark Brown Chernozem	17 April	5 Aug	116	
	2016	49°40'N 112°31'W	Typic Boroll	Dark Brown Chernozem	13 April	16 Aug	251	

† Observed precipitation from seeding to harvest. This includes precipitation and irrigation at Lethbridge Irrigated site

‡ Long term average precipitation calculated from April 1 to Sept 15 using 30 year historical data interpolated from the nearest geographical provincial weather station (Alberta Agriculture and Forestry, 2016).

Table 4-2. Soil descriptions and nutrient properties before fertilizer application at two sample depths for each site-year.

Site	Year	Soil Properties													
		pH		CEC†		OM‡		NO_3–N§		P¶		K#		S††	
		Sample Depth‡‡													
		cm													
		0-15	16-30	0-15	16-30	0-15	16-30	0-15	16-30	0-15	16-30	0-15	16-30	0-15	16-30
				--cmol kg^{-1}--		------%------		---------- mg kg^{-1} ----------							
Bon Accord	2014	6.3	6.9	23.2	22.5	9.6	5.0	10	16	21	19	167	107	32	118
Rainfed	2015	5.4	6.4	26.4	23.5	8.7	6.3	9	1	24	12	218	129	16	11
	2016	5.1	5.8	26.6	17.5	7.0	5.6	20	5	18	16	107	89	23	15
Falher	2014	6.1	6.9	13.2	19.1	4.8	2.3	10	10	24	-	226	176	15	14
Rainfed	2015	5.7	6.2	9.1	14.8	2.7	2.4	20	17	17	0	106	96	10	12
	2016	5.6	5.8	17.1	22.8	5.3	3.1	11	8	30	8	244	114	16	14
Killam	2014	5.1	6.0	15.1	10.6	4.5	2.4	11	8	48	20	261	112	18	16
Rainfed	2016	5.3	5.6	16.9	17.8	5.2	3.0	12	5	37	20	228	104	19	13
Lethbridge	2014	7.9	8.1	35.2	39.8	4.2	2.7	8	26	9	5	251	265	11	25
Irrigated	2015	7.5	7.8	31.8	40.4	3.8	3.1	13	26	39	14	330	299	18	40
	2016	7.2	7.7	28.9	34.1	3.4	2.7	18	16	31	14	345	379	17	47
Lethbridge	2014	6.9	7.5	24.8	37.8	4.2	2.7	1	2	15	6	348	262	16	29
Rainfed	2015	7.7	7.8	43.3	44.5	3.9	2.9	6	9	7	2	350	303	8	21
	2016	6.9	7.7	24.5	34.0	3.0	2.2	7	7	16	11	385	376	26	95

† Cation exchange capacity
‡ Soil organic matter
§ Nitrate nitrogen
¶ Phosphorus (bray)
# Potassium
†† Sulfur
‡‡ 0-15 and 15-60cm at Lethbridge irrigated and rainfed sites

Table 4-3. Seeding equipment and plot area information for each site-year.

Site	Year	Seed Drill Type	Opener Type	Fertilizer Placement	Row Spacing	Number of Rows	Seeded Plot area
					---m---		----m^{-2}---
Bon Accord	2014	Air seeder	Atom Jet hoe	Side band†	0.20	8	10.9
Rainfed	2015	No-till box seeder	Double disc	Mid-row band‡	0.25	6	10.2
	2016	No-till box seeder	Double disc	Mid-row band	0.25	6	10.2
Falher	2014	No-till box seeder	Double shoot hoe	Side band	0.23	6	11.7
Rainfed	2015	Air seeder	Double shoot hoe	Side band	0.23	6	11.7
	2016	Air seeder	Double shoot hoe	Side band	0.23	6	11.7
Killam	2014	Air seeder	Atom Jet hoe	Side band	0.20	8	10.9
Rainfed	2016	No-till box seeder	Double disc	Mid-row band	0.25	6	10.2
Lethbridge	2014	No-till box seeder	John Deere 90 series disc	Side band	0.25	8	20.0
Irrigated	2015	No-till box seeder	John Deere 90 series disc	Side band	0.25	8	20.0
	2016	No-till box seeder	John Deere 90 series disc	Side band	0.25	8	20.0
Lethbridge	2014	No-till box seeder	John Deere 90 series disc	Side band	0.25	8	20.0
Rainfed	2015	No-till box seeder	John Deere 90 series disc	Side band	0.25	8	20.0
	2016	No-till box seeder	John Deere 90 series disc	Side band	0.25	8	20.0

† Side banding placed fertilizer 5cm to the side and 2cm below the seed

‡ Mid-row banding placed fertilizer 12.5cm to the side and 4cm below the seed

Table 4-4. Yield goals representing the 10-year average feed barley yield of the land co-operator at each site-year that were used to determine fertilization rates and rate of N, P, K, and S applied at seeding for each site-year.

			Nutrient Applied			
Site	**Year**	**Yield Goal**	**N†**	**P_2O_5‡**	**K_2O§**	**S¶**
		---MT ha^{-1}---	----------Kg ha^{-1}----------			
Bon Accord	2014	4.8	88	50	22	17
Rainfed#	2015	4.8	120	50	22	0
	2016	4.8	102	34	67	5.5
Falher	2014	4.5	108	56	22	22
Rainfed	2015	4.5	90	34	28	28
	2016	4.5	68	39	22	17
Killam	2014	5.6	130	22	22	5
Rainfed	2016	5.6	161	17	22	6
Lethbridge	2014	6.3	123	55	0	0
Irrigated	2015	5.5	66	30	0	0
	2016	5.5	81	35	0	0
Lethbridge	2014	3.8	95	25	0	0
Rainfed	2015	3.8	75	45	0	0
	2016	3.8	77	35	0	0

† Nitrogen
‡ Phosphorus
§ Potassium
¶ Sulfur
# Co-operator had no record of feed barley yield and so their long term malt barley yield average was adjusted for the differential between the AFSC (Agriculture Financial Services Corporation, 2014) Risk Area yield average for feed and malt barley.

Table 4-5. Pre-emergence and in-crop herbicide active ingredients, application dates, and application rates for weed control in all plots at 15 site-years.

Site	Year	Pre-emergence weed control		In-crop weed control	
		Active ingredients	Application date	Active ingredients	Application date
Bon Accord	2014	Glyphosate†, saflufenacil‡	13 May	Florasulam§, fluroxypyr¶, MCPA ester#, pinoxaden††	11 June
Rainfed	2015	Glyphosate, saflufenacil	4 May	Florasulam, fluroxypyr, MCPA ester, pinoxaden	5 June
	2016	Glyphosate, saflufenacil	4 May	Florasulam, fluroxypyr, MCPA ester, pinoxaden	31 May
Falher	2014	Glyphosate, saflufenacil	21 May	Fluroxypyr, clopyralid, pinoxaden	14 June
Rainfed	2015	Glyphosate	6 May	Florasulam, fluroxypyr, MCPA ester, pinoxaden	8 June
	2016	Glyphosate, tribenuron-methyl	2 May	Florasulam, fluroxypyr, MCPA ester, pinoxaden	5 June
Killam	2014	Glyphosate, tribenuron-methyl‡‡	23 May	Florasulam, fluroxypyr, MCPA ester, pinoxaden	12 June
Rainfed	2015	Thifensulfuron-methyl§§, tribenuron-methyl	14 May	Florasulam + clopyralid¶¶ + MCPA ester	11 June
	2016	Glyphosate, saflufenacil	13 May	Florasulam, fluroxypyr, MCPA ester, pinoxaden	18 June
Lethbridge	2014	Glyphosate, saflufenacil	28 April	Florasulam, MCPA ester, pinoxaden	6 June
Irrigated	2015	Glyphosate, saflufenacil	21 April	Florasulam, MCPA ester, pinoxaden	27 May
	2016	Glyphosate, saflufenacil	8 April	Florasulam, MCPA ester, pinoxaden	16 May
Lethbridge	2014	Glyphosate, saflufenacil	13 May	Florasulam, MCPA ester, pinoxaden	23 June
Rainfed	2015	Glyphosate, saflufenacil	15 April	Florasulam, MCPA ester, pinoxaden	25 May
	2016	Glyphosate, saflufenacil	18 April	Florasulam, MCPA ester, pinoxaden	25 May

† Glyphosate applied at 360 g ae ha^{-1} rate
‡ Saflufenacil applied at 18 g ae ha^{-1} rate
§ Florasulam applied at 2.5 g ae ha^{-1} rate
¶ Fluroxypyr applied at 99 g ae ha^{-1} rate at all site-years except Falher 2014 where it was applied at 140 g ae ha^{-1} rate
# MCPA ester applied at 356 g ae ha^{-1} rate
†† Pinoxaden applied at 61 g ae ha^{-1} rate
‡‡ Tribenuron-methyl applied at 7.4 g ae ha^{-1} rate
§§ Thifensulfuron-methyl applied at 9.9 g ae ha^{-1} rate
¶¶ Clopyralid applied at 99 g ae ha^{-1} rate

Table 4-6. Insecticide active ingredient, application rate, and application date at site-years requiring insect pest control in the trial area.

Site	Year	Insect controlled	Active ingredient applied	Application rate	Application date
				-----g ae ha^{-1}-----	
Bon Accord	2015	*Melanoplus* spp.	Chlorpyrifos†	396	15 June
Bon Accord	2016	*Oulema melanopus* L.	Malathion‡	556	23 June
Bon Accord	2016	*Melanoplus* spp.	Chlorpyrifos	396	18 July
Falher	2016	*Euxoa* spp.	Chlorpyrifos	117	14 June

† (*O, O*-diethyl *O*-3,5,6-trichloro-2-pyridinyl phosphorothioate)

‡ 2-[(dimethoxyphosphorothioyl)sulfanyl]butanedioate

Table 4-7. ANOVA *P* values and variance estimates and *P* values for orthogonal contrast statements for the effect of post-emergence N applied just prior to BBCH 30 and seeding rate x PGR x fungicide (SRxPGRxFung) combinations on feed barley agronomic variables collected at 14 Alberta environments. Environments (location and year), replicates within environments and their interactions with fixed effects were considered random.

Effects	Spike length	NDVI†	Height	Lodging‡	Maturity	Grain yield	Kernel weight	Test weight	Grain protein	N yield	Grain starch	ADF§	NDF¶
	cm		cm		days	MT ha^{-1}	g	kg hl^{-1}	mg g^{-1}	kg ha^{-1}		%	
Post-emergence N (N)	0.596	**0.050**	**0.003**	0.712	**0.015**	**0.005**	0.574	0.620	**<0.001**	**<0.001**	**<0.001**	0.837	0.086
Environment#	<1	<1	101**	<1	56	2**	7	7*	1**	882**	<1**	<1**	<1**
Environment x N††	3	1**	<1	8	<1	1**	<1	<1	2**	2**	1	<1	<1
Adjusted CV (%)	8.9		4.5	21.3	1.2	6.4	2.8	2.1	4.0	7.5	1.7	3.1	1.8
Contrasts ‡‡													
Linear N	0.233	**0.014**	**<0.001**	0.316	**0.013**	**<0.001**	0.655	0.912	**<0.001**	**<0.001**	**<0.001**	0.599	**0.022**
Quadratic N	0.950	0.169	0.087	0.941	**0.033**	0.466	0.475	0.471	0.146	0.141	**0.023**	0.842	0.968
N vs. N + NBPT	0.511	0.881	0.676	0.649	0.470	0.665	0.264	0.271	0.571	0.413	0.762	0.472	0.244

** *P* value <0.01

† Normalized difference vegetation index

‡ Lodging index (Berry et al., 2003). Lodging data was transformed using log10 transformation to achieve normality

§ Acid detergent fiber

¶ Neutral detergent fiber

Variance estimate for the environment random effect.

†† Percentage of the variance associated with the environment × post-emergence N was calculated as follows: [(variance estimate for environment x post-emergence N)/(sum of all variance estimates including environment)]x 100.

‡‡ Linear and quadratic contrasts compared the 0, 34, and 68 kg ha^{-1} N levels, but not the 34 kg ha^{-1} N + Agrotain level

Table 4-8. LS means for the levels of post-emergence N applied just prior to BBCH 30 for agronomic response variables across 14 site-years.

Post-emergence N level	Spike length	NDVI†	Height	Lodging‡	Maturity	Grain yield	Kernel weight	Test weight	Grain protein	N yield	Grain starch	ADF§	NDF¶
	cm		cm		days	MT ha^{-1}	g	kg hl^{-1}	mg g^{-1}	kg N ha^{-1}	----------%----------		
0 kg ha^{-1} N	6.2	0.407	70.9	9	98.1	6.75	44.6	63.7	108	125	60.1	5.72	18.82
34 kg ha^{-1} N	6.2	0.414	71.7	11	98.2	6.99	44.7	63.6	112	133	59.8	5.72	18.77
68 kg ha^{-1} N	6.2	0.425	72.8	11	98.9	7.11	44.6	63.7	115	138	59.6	5.72	18.76
34 kg ha^{-1} N + NBPT	6.2	0.416	71.6	11	98.2	6.92	44.4	63.9	111	130	59.9	5.71	18.76
ddf##	39	27	39	6	24	39	27	33	39	39	39	39	39

† Normalized difference vegetation index

‡Lodging index of 0-100, where 0= upright and 100=completely lodged (Berry et al., 2003).

§ Acid detergent fiber

¶ Neutral detergent fiber

Denominator degrees of freedom

Table 4-9. Post-emergence N application date and environmental conditions on and after date of post-emergence N application.

Location	Year	Post-emergence N date†	Max temp‡	Relative humidity§	Small rainfall events¶	Days to 5mm rainfall#
			◦C	%		
Bon Accord Rainfed	2014	13 June	21	50	3	6
	2015	9 June	27	52	0	2
	2016	8 June	22	67	1	3
Falher Rainfed	2014	21 June	21	37	4	>10
	2015	15 + 16 June	20	64	1	>10
	2016	20 June	25	66	0	1
Killam Rainfed	2014	22 June	23	56	1	3
	2016	21 June	26	68	0	0
Lethbridge Irrigated	2014	12 June	21	57	0	1
	2015	2 June	17	78	2	2
	2016	31 May	21	49	0	2
Lethbridge Rainfed	2014	23 June	24	64	4	>10
	2015	4 June	23	56	1	>10
	2016	1 June	25	53	1	>10

†Date of post-emergence N application

‡Maximum air temperature on the date of post-emergence N application

§ Average daily relative humidity at 2m on the date of post-emergence N application

¶ Number of <5mm rainfall events before a 5mm rainfall event occurred, up to 10 days following post-emergence N application determined from the nearest provincial weather station(Alberta Agriculture and Forestry, 2016b)

#Number of full days with no significant rainfall (< 5mm) following post-emergence N application, determined from the nearest provincial weather station (Alberta Agriculture and Forestry, 2016b)

Table 4-10. NDVI measurements on post-emergence N treatments two and ten days UAN application in the 2nd and 3rd replicates excluding plant growth regulator treatments at Bon Accord 2015.

Post-emergence	NDVI†	
N level	2 DAA	10 DAA
0	0.476	0.655
34	0.449	0.624
68	0.456	0.629
34 + NBPT	0.469	0.649

† NDVI readings (n=16) averaged across seeding rates, excluding the PGR treatments.

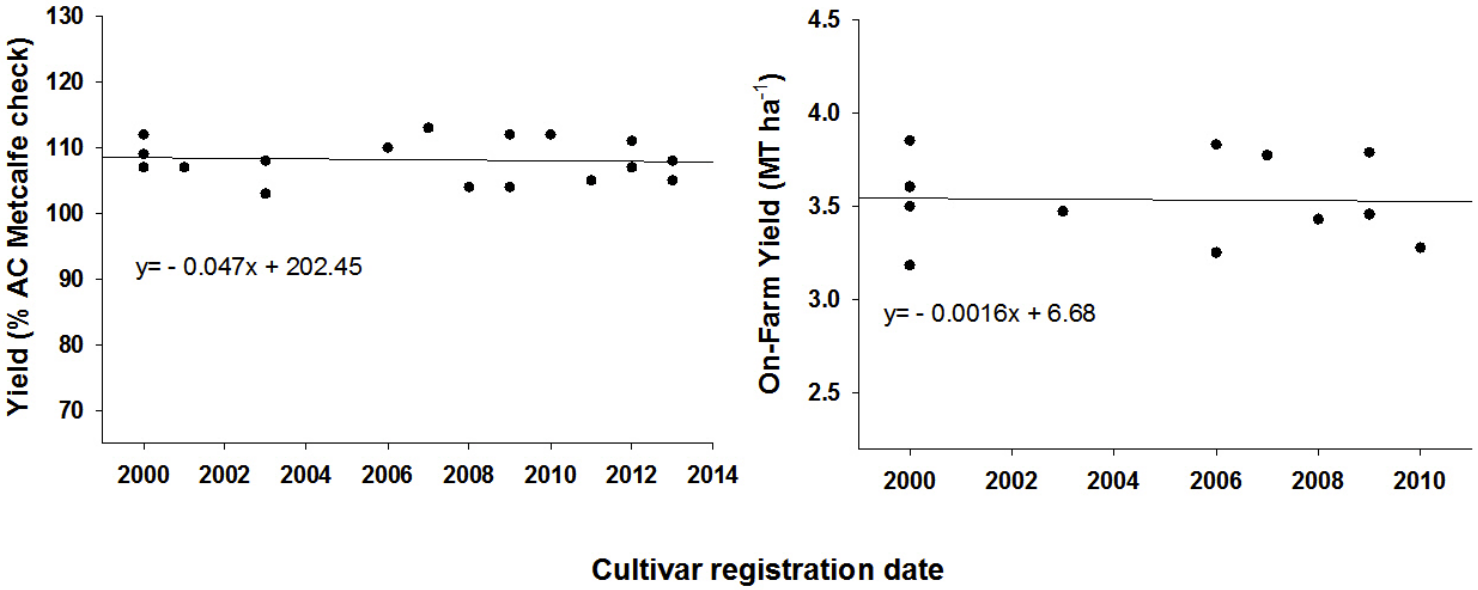

Figure 4-1. (a) Performance of hulled two-row and six-row feed barley cultivars registered between 2000 and 2013 in the Alberta Regional Variety small-plot trials. Adapted from Alberta Agriculture and Forestry (2016a)**. (b) Six-year average on-farm grain yield for the 2010-2015 growing seasons of hulled two-row and six-row feed barley cultivars registered between 2000 and 2010 under Alberta rain-fed production. Adapted from Agriculture Financial Services Corporation (2016).**

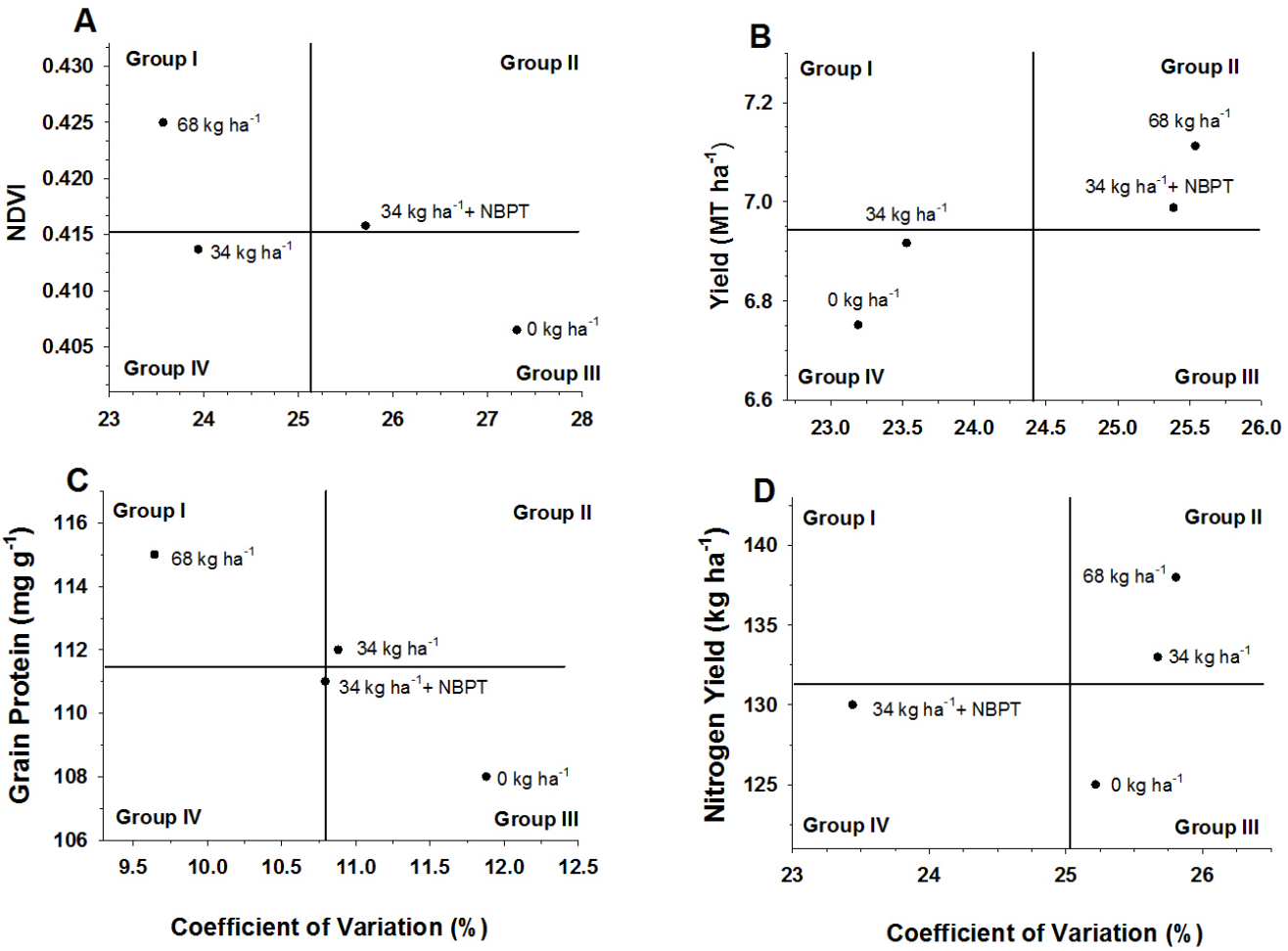

Figure 4-2. Biplots summarizing NDVI (a), grain yield (b), grain protein (c), and grain N yield (d) means vs. CV for post-emergence N levels across 14 Alberta environments. Grouping categories: Group I: high mean, low variability; Group II: high mean, high variability; Group III: low mean, high variability; Group IV: low mean, low variability.

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Chapter Five: Effect of cultivar and agronomic management on feed barley production in Alberta

5.1. Introduction

Alberta produces the majority of Canada's barley and barley is the second-most grown small grain cereal crop in the province. Feed barley production supports a large cattle industry of about 1.7 million steers and heifers in Alberta (Statistics Canada, 2016a). Barley also contributes to crop diversity in western Canada, where the crop rotation in nearly half of 223 surveyed fields in Alberta consisted of canola grown frequently, once every 2 years (personal communication, Julia Leeson, 2017). Long and diverse crop rotations are desirable because of decreased disease and insect pest risk and higher grain yield (Harker et al., 2014; O'Donovan et al., 2014; Turkington et al., 2012). While barley accounted for an average of 20% (1.53 million ha) of the seeded area in Alberta between 2006 and 2016, provincial barley acres have declined steadily by 34% during this period, from a high of 1.96 million ha in 2007 to a low of 1.29 million ha in 2014 and 2016 (Statistics Canada, 2016b). In addition, small-plot and on-farm yield data suggest the yields of feed barley cultivars registered from 2000 to 2013 have been stagnant (Figure 5.1a, 5.1b) (Agriculture Financial Services Corporation, 2016; Alberta Agriculture and Forestry, 2016a). Although on-farm yield data contains biases such as differential management and cultivar acreage, these data suggest that the yield performance of feed barley cultivars registered between 2000-2013 have not improved significantly. High yields are required to balance low commodity prices for feed barley profitability. Therefore, static on-farm yields of feed barley cultivars could be a contributing factor for reduced barley acreage in the province.

In addition to herbicidal weed control, current feed barley management practices in Alberta, which differ from malt barley management practices mainly in N amount, involve 100% of applied N requirements met at the time of seeding, no plant growth regulator use, and foliar fungicide use occasionally if environment and crop history necessitates. Furthermore, these practices are not applied in a cultivar-specific manner. To keep feed barley a competitive crop in the western Canadian rotation, research was conducted to determine the effect of advanced agronomic management practices on feed barley production. Understanding whether the response of feed barley to management is cultivar specific may improve yields and is necessary to target the efficient use of crop inputs.

In addition to increasing grain yields, improving the quality of feed barley through cultivar selection and management is desirable. The quality parameters of feed barley differ from the low protein requirements defining malt barley quality, and feed barley quality response to agronomic management has been the subject of limited research. Starch and fiber content are parameters defining feed quality. High starch content is desirable because of its high digestibility and positive correlation with weight gain in feedlot cattle (Surber et al., 2000). Conversely, acid detergent fiber (ADF) is comprised of cellulose and lignin and a negative correlation was reported between ADF and digestibility (Engstrom et al., 1992). Surber et al. (2000) reported ADF and starch content were negatively correlated, and that barley feed quality could be improved by selecting for high starch and low ADF content. Neutral detergent fiber (NDF) is comprised of the cell wall components cellulose, lignin, and hemicellulose. Barley cultivars with low NDF and high starch content tended to have improved digestibility, energy content, and feed efficiency when fed to feedlot cattle,

although NDF digestibility was also an important factor (Ovenell-Roy et al., 1998b). Previous studies have reported variation in the starch and fiber composition of barley across cultivars and environments in Manitoba (Campbell et al., 1995) and Washington, USA (Ovenell-Roy et al., 1998a). However, little information is available for the starch and fiber composition of Alberta feed barley cultivars and the effect of agronomic management on feed grain quality has not been widely studied in western Canada.

Aside from moisture content and weed seed dockage, test weight is the main parameter used by feedlot operators to determine barley quality (Grimson et al., 1987). The Canada Grains Act (1970) specifies test weight must be 59 kg hL^{-1} to meet the standard for Canada No. 1 feed barley. Low test weight barley was less digestible than high test weight barley, which was indicative of higher ADF and NDF concentrations in the low test weight barley (Yang et al., 2013). Low test weight barley has increased processing requirements and requires increased equipment handling capacity, resulting in increased costs (Mathison, 2000). Grimson et al. (1987) reported 1.2% more dry matter was required for weight gain in feedlot steers for each kg hL^{-1} decrease in barley test weight ranging from 48 to 56 kg hL^{-1}. Feeding high test weight barley provides feed efficiency and cost savings for feedlots, and barley growers avoid price discounts associated with low test weight feed barley.

Agronomic management practices such as post-emergence nitrogen (N) application and foliar fungicides are available to western Canadian farmers to optimize feed barley yield. Additionally, plant growth regulators (PGRs) to reduce lodging are becoming available. Examining barley cultivar response to these practices may increase feed barley quality and address existing production constraints that result in lower yields.

Barley yield responds positively to increasing N fertilizer rates applied at seeding when moisture is not limiting and responses are often cultivar specific. Cultivar specific responses to spring applied N in Western Canadian spring barley occurred for lodging (O'Donovan et al., 2015), grain yield (Grant et al., 1991b; McKenzie et al., 2004b), grain protein (Grant et al., 1991a; McKenzie et al., 2004b; O'Donovan et al., 2011), and kernel weight (O'Donovan et al., 2011). Nitrogen applied at BBCH 30 (Lancashire et al., 1991) increased grain yield more often than N applied at BBCH 22 or when all N was applied at seeding, if there was sufficient initial N to support early season growth in Uruguay, under high growing season precipitation (>500mm) conditions (Baethgen et al., 1995). Maximum yield increases occur when N is not limited at the time of maximum crop uptake, which begins at stem elongation (BBCH 30) in cereals (Baethgen and Alley, 1989; López-Bellido et al., 2005; Mossedaq and Smith, 1994). Western Canadian studies examining the response of local barley cultivar: grain yield, grain quality, lodging, and maturity responses to post-emergence N at the beginning of stem elongation have not been conducted.

Lodging is a production constraint in Alberta because of reduced grain yield, lower grain quality, and harvest inefficiency. Lodging of barley during early and mid grain-fill stages resulted in 1.7 and 1.2 MT ha^{-1} (up to 40%) grain yield losses in Alberta (Briggs, 1990; Jedel and Helm, 1991). Grain yield is lost when lodging reduces canopy photosynthesis and photosynthetic transport during grain-fill, and also when lodging results in increased disease (Berry and Spink, 2012; Setter et al., 1997). Yield is also lost when grain spike height is too low for mechanical harvest (Pinthus, 1973). Lodging also results in test weight decreases (Baethgen et al., 1995) and increased risk of fungal infection of the grain (Berry et al., 2004).

Harvest operations are slowed in a lodged crop and harvest costs can increase by up to 50%, as a result of lodging (Rademacher, 2009). Conditions conducive to lodging are often similar to conditions required for high grain yield: high rainfall or irrigation, and high N fertility (Berry et al., 2000; Caldwell, 1983; O'Donovan et al., 2015; Rajkumara, 2008). The use of PGRs may reduce lodging while maintaining yield. Chlormequat chloride (CCC) is a gibberellic acid biosynthesis inhibiting PGR used to reduce height and lodging that was recently registered for use on wheat in Western Canada, formulated as Manipulator (Taminco US Inc., 2015). Studies from Eastern Canada reported that barley height response to CCC applied at the beginning of stem elongation was variable across environments and cultivars(Clark and Fedak, 1977; Ma and Smith, 1992a). The effect of CCC applied on Alberta barley cultivars on height, lodging, grain yield, and grain quality is unknown.

Multiple western Canadian studies report positive barley grain yield or test weight response to foliar fungicide application, depending on cultivar, when disease pressure and environmental conditions are favourable for disease development (Kutcher et al., 1999; 2012; 2011; Turkington et al., 2015; 2012). Kutcher and Kirkham (1997; 2012) reported foliar fungicide increased grain yield, test weight, and kernel weight by up to 37%, 5%, and 11%, respectively, in a barley cultivar lacking genetic disease resistance, while small or not significant (NS) yield, test weight, or kernel weight increases occurred in barley cultivars with improved genetic disease resistance. Therefore, the magnitude response of recently released barley cultivars to foliar fungicide may vary according to genetic disease resistance and environmental conditions.

The yield, quality, and agronomic responses of feed barley cultivars to multiple advanced management practices including: CCC, post-emergence N, and foliar fungicide is unknown in the variable climatic and edaphic conditions found across Alberta. The objectives of this study were: (a) to determine the effect of feed barley cultivar (genotype) and advanced agronomic management (post-emergence N, CCC, and foliar fungicide application) on agronomic, grain yield, and grain quality responses; (b) to determine if responses to advanced agronomic management are barley cultivar specific; and (c) to determine the influence of environment on feed barley responses to cultivar and agronomic management.

5.2. Materials and Methods

Field experiments were conducted over three growing seasons from 2014-2016 at four rainfed and one irrigated site in the major agro-climatic zones of Alberta, Canada, under no-tillage management (Table 5.1). Soil was sampled prior to seeding (Table 5.2). Growing season precipitation was acquired from the nearest weather station (Table 5.1).

Seeding rates were calculated using thousand-kernel weight, germination percent, and predicted emergence mortality (10%) to achieve a target plant stand density of 355 plants m^{-2}. All treatments were direct seeded at a depth to reach soil moisture (2.5 to 3.8cm seeding depth range) into canola (*Brassica napus* L.) stubble. Seed was treated with difenoconazole {1-(2-[4-(chlorophenoxy)-2-chlorophenyl-(4-methyl-1,3-dioxolan-2-yl)-methyl])-1H-1,2,4-triazole}, metalaxyl [N-(2,6-dimethylphenyl)-N-(methoxyacetyl)-alanine methyl ester], and sedaxane (N-[2-[1,1'-bicyclopropyl]-2-ylphenyl]-3-(difluoromethyl)-1-methyl-1H-pyrazole-4-carboxamide) formulated as Vibrance XL (Syngenta Canada Inc.).

Opener type, fertilizer placement, row spacing, and seeded plot size varied between location and years (Table 5.3). Appropriate fertilizer rates at seeding were determined using soil test results (Table 5.2) and yield targets were calculated using the land co-operator's 10-year feed barley yield average (Table 5.4). Nitrogen, P, K, and S were applied at seeding as granular fertilizer in the form of urea (46-0-0-0), mono-ammonium phosphate (11-52-0-0), potassium (0-0-60-0), and ammonium sulfate (21-0-0-24) (Table 5.4). Seed safe levels of P were applied in the seed row (22 kg ha^{-1} at Falher, Bon Accord, and Killam; 45kg ha^{-1} at Lethbridge rainfed, and 30kg ha^{-1} at Lethbridge irrigated) and the remaining, if required, was side banded or mid-row banded with the N, K, and S fertilizer. Herbicides were applied pre-emergence and in-crop as required for weed control (Table 5.5). Insecticide was applied to trial areas as required to control insect pests (Table 5.6). Seeding and harvest dates varied between site and year (Table 5.1). Glyphosate (N-(phosphonomethyl)glycine) was applied pre-harvest at 360 g ae ha^{-1} rate when grain moisture content was < 30% to assist with harvest management.

The experimental design was a split-plot with four replicates. The ten feed barley cultivars (Table 5.7) were allocated to main plots and management levels (standard or advanced) were allocated to sub-plots. Feed barley cultivars were selected based on: i) acreage grown in Alberta; ii) date of registration; and iii) agronomic characteristics such as height, lodging resistance, and disease resistance. The standard level of management received no additional in-season inputs apart from herbicide and insecticide application. The advanced level of management was comprised of: additional 34 kg ha^{-1} post-emergence N in the form of undiluted urea ammonium nitrate (UAN, 28-0-0) with a urease inhibitor applied

just prior to BBCH 30 (Lancashire et al., 1991); the PGR chlormequat chloride (CCC) applied at BBCH 31 to BBCH 33, depending on cultivar development at the time of application; and two foliar fungicide applications comprised of different active ingredients at BBCH 39 and two weeks later (Table 5.8). Details of advanced management product rates, chemical names and calendar application dates are listed in Table 5.8. Fungicides were applied at the recommended rates, at 200 L ha^{-1} water volume. Post-emergence N was applied using TeeJet StreamJet SJ3-015 nozzles, CCC was applied using TeeJet 30-015 nozzles and fungicides were applied using John Deere Twin Air 02 nozzles. A fungicide application rate error occurred at Killam in 2015 and treatment results from this site-year were excluded from data analysis.

Barley stand density was determined 2 weeks after emergence by counting plants in two 1-m row lengths in each plot. Plant height was quantified after BBCH 83 by measuring the height of 4 main tillers from the inner plot rows from the ground to the top of the spike (excluding awns). To quantify greenness differences between treatments, normalized difference vegetation index (NDVI) of plots was measured using a handheld GreenSeeker (Trimble Navigation Ltd, Sunnyvale, CA) between BBCH 83 and 85. Five flag and 5 penultimate leaf samples were collected from the inner rows of each plot from all treatments in the 2nd replicate 7-10 days after the 2nd fungicide application. The percent leaf area infected by fungal disease was estimated visually and disease symptomology was used to determine causal pathogen species. If disease symptomology was insufficient to determine the pathogen species, the pathogen was plated on 10% V-8 tomato juice agar as per Tekauz (1990) and identified visually using a microscope. Ten main stem heads from each plot were collected at 30 to 40% grain moisture and days to maturity were determined

according to Karamanos et al. (2008). Lodging index (Berry et al., 2003) was measured at physiological maturity. Grain was harvested using Wintersteiger Delta small plot combines (Wintersteiger Inc., Saskatoon, Canada) with 2012 classic grain gauge automatic weigh systems at physiological maturity. Test weight was either automatically determined by the combine weigh system or measured using a GAC 2100 Dickey-john grain moisture tester (Churchill Industries, Minneapolis, MN). Kernel weight (g thousand-kernels^{-1}) was determined by weighing 500 kernels and multiplying the resulting weight by 2. Grain protein, starch, acid detergent fiber (ADF), and neutral detergent fiber (NDF) concentrations were determined with a DS2500 near infrared reflectance (NIR) spectrometer (FOSS, Eden Prairie, MN 55344, USA). Grain yield, test weight, kernel weight, and NIR data were adjusted to the Canadian Grain Commission standard 14.8% grain moisture. Nitrogen yield was determined by multiplying grain yield x percent nitrogen in the grain, as determined by NIR analysis. Composite samples were graded by the Canadian Grain Commission to determine feed barley grade. Due to various logistical constraints, not every category of data was collected at every site year.

Data were analyzed using PROC MIXED of SAS version 9.4 (SAS Institute Inc., 2014). Lodging data was transformed using the log10 data transformation to achieve normality, and least significant means were reported as the back transformed values. Cultivar (main plot) and management (sub plot) were considered fixed effects. Location by year combinations (14 site-years), replicates within site-years, and site-year interactions with fixed effects were considered random. A repeated statement for site-year was included in the model to account for heterogeneity of variance between site-years. By considering site-year and the

interactions between site-year and the treatments (fixed effects) as random, future performance of treatments at untested locations may be inferred, and the large number of site years analyzed (14) facilitated this approach (Yang, 2010). Barley cultivar and management means were compared using Fisher's Protected LSD test (α 0.05). Correlation between response variables was determined using Pearson's correlation coefficient.

Environment (site-year) interactions with treatments were assessed using the Wald Z test to determine if variance estimates were different than zero at an α level of 0.01. The relative size of the variance estimate for the environment by cultivar (ExC) or environment by management (ExM) interactions compared with the sum of the variance estimates for all effects including environment was also used to determine the importance of the random environment by treatment interactions (HP Piepho, personal communication, 2017). Environment interactions with treatments were considered large if the relative size of the variance estimate for the ExC or ExM interaction compared with the sum of the variance estimates for all effects including environment was >10%.

When the ExC or ExM variance estimates were relatively large or significant, a grouping methodology, as previously described by Francis and Kannenberg (1978), was used to explore treatment responses and variability. The mean and coefficient of variation (CV) were estimated for treatments across years and replicates. Means were plotted against CV for response variables that had a large or significant ExC or ExM variance estimate, and the overall mean of means and CVs was included in the plot to categorize the data into four categories: Group I: High mean, low variability; Group II: High mean, high variability; Group III: Low mean, high variability; and Group IV: Low mean, low variability.

5.3. Results and Discussion

5.3.1. Environmental Conditions

Growing season precipitation ranged from below the thirty-year average for the location (101mm) to above average (502mm) across the 14 environments (Table 5.1). Plant stand densities were within 7% of the target 355 plants m^{-2} in 5 environments, and at other environments they were adequate but not measured or measured too early (data not shown). Leaf disease assessments showed fungal disease was present in all but 1 environment at varying levels; however, the overall level of disease was low in the study, especially in environments with below average precipitation (Table 5.9). The predominant diseases were net-form net blotch (*Drechslera teres f. teres* (Sacc.) Shoemaker), spot-form net blotch (*Drechslera teres f. maculata* Smedeg.), spot blotch (*Cochliobolus sativus* (Ito and Kuribayashi) Drechs. ex Dastur), and stripe rust (*Puccinia striiformis spp.*), with less frequent occurrence of scald (*Rhynchosporium commune* Zaffarano, McDonald and Linde sp. nov. (formerly known as *Rhynchosporium secalis* (Oudem.) J. J. Davis)) (Table 5.9). As expected from the diverse precipitation across the 14 environments in the study, most variables varied between environments, as indicated by large (≥10) or significant ($p<0.01$) environment variance estimates (Table 5.10). Plant height, days to maturity, grain yield, and N yield were higher and protein tended to be lower in environments with more growing season precipitation (data not shown).

5.3.2. Effect of Cultivar

There were significant differences between cultivars for all measured agronomic variables (Table 5.10). Six-row cultivars were generally shorter than two row-cultivars with the exceptions of Breton, a tall six-row, and CDC Coalition, a short two-row (Table 5.11). Jedel and Helm (1994a) reported six-row cultivars were slightly taller than two-row cultivars, with the height of both row types decreasing over time of cultivar registration (1910-1987). Our results suggest six-row cultivar height decrease has been generally greater over recent time than that of two-row. There was a small positive correlation between lodging and height (R^2=0.28) indicating additional factors influence lodging resistance such as culm diameter (Jedel and Helm, 1994a). The cultivar with the least lodging was CDC Coalition, while Breton, Gadsby, and Xena had the highest. All other cultivars had intermediate lodging (Table 5.11).

NDVI differed between cultivars (Table 5.11) but it was not a consistent indicator of grain yield for cultivars (R^2= 0.23), whereas NDVI was more strongly positively correlated to maturity (R^2=0.66). The NDVI collection time may have been after the beginning of leaf senescence for earlier maturing cultivars, thereby weakening the correlation of NDVI to grain yield. Yield-influencing events such as lodging after NDVI have been reported to weaken correlation of grain yield and NDVI in winter wheat (Raun et al., 2001). Differential lodging and maturity between barley cultivars likely contributed to the weak correlation between feed barley yield and NDVI across cultivars.

Maturity ranged from 96 to 102 days depending on cultivar (Table 5.11). CDC Austenson, Gadsby, and Amisk matured at least 4 days later than all other cultivars. Advanced

management lengthened maturity by an average of 1 day across cultivars (Table 5.11). However, there was a significant interaction between cultivar and management for maturity (Table 5.10). Maturity lengthened by less than 1 day in cv. Busby, CDC Coalition, and Gadsby, while all other cultivars lengthened maturity between 1 and 2 days in response to advanced management (data not shown). However, the maturity for all cultivars under advanced management was within the frost-free period of 115 to 125 days where the study was conducted(Alberta Agriculture and Forestry, 2016c), so the larger maturity increase observed in some cultivars was not a production constraint in western Canadian growing environments.

Grain yield differed between cultivars, and higher yielding cultivars tended to have higher kernel weights, except for Gadsby, which had the highest kernel weight but was low yielding (Table 5.11). The highest yielding cultivars were the two-row cultivars: CDC Austenson, Xena, and CDC Coalition (Table 5.11). This finding agrees with provincial crop insurance on-farm yield data from 2012-2015 that showed CDC Austenson, CDC Coalition, Champion, and Xena were the top 4 yielding feed cultivars in Alberta grown under rainfed production (Agriculture Financial Services Corporation, 2016). Of concern, the cultivars Amisk, Breton, Gadsby, Busby, and Muskwa, registered between 2008 and 2013 (Table 5.7) yielded between 3 to 8% lower than the cultivars registered 8 to 13 years earlier (Vivar and Xena), and the cultivars CDC Austenson, CDC Coalition, and Champion yielded similar to Vivar and Xena (Table 5.11). The highest yielding cultivar, CDC Austenson, yielded 2.9% and 3.4% higher than Xena and Vivar, respectively. On-farm rainfed yield data from the 2010-2015 growing seasons and small plot yield data from the Alberta Regional Variety Trials support

this finding of static or declining feed barley yields with advancing year of registration in Alberta between 2000 and 2013 registration dates (Figure 5.1a and 5.1b) (Agriculture Financial Services Corporation, 2016; Alberta Agriculture and Forestry, 2016a). In contrast, Jedel and Helm (1994b) reported 13 to 41 kg ha^{-1} $year^{-1}$ grain yield advances of 20 Western Canadian feed barley cultivars registered from 1910 to 1987. In the present study, CDC Austenson was the only cultivar that met the rate of yield advance reported by Jedel and Helm (1994b), while all other cultivars showed static or negative yield advances. It appears that producer acres are reflective of the yield gap between two and six-row cultivars in the province, with six-row cultivars comprising just 4% of insured Alberta dryland feed barley acres in 2015 (Agriculture Financial Services Corporation, 2016)

Grain N yield and protein concentration varied between cultivars (Table 5.10). Higher yielding cultivars generally had higher grain N yield (correlation: R^2= 0.92; *P*<0.001), and differences in grain N yield between cultivars generally followed similar patterns to the grain yield differences between cultivars (Table 5.11). Exceptions occurred with Gadsby, which had higher N yield despite low grain yield because of high grain protein concentration, and Vivar, which had low N yield despite higher grain yield because of low grain protein. As expected, cultivars with high grain yield tended to have lower protein concentration (Table 5.11 and 5.12). The negative relationship between grain yield and protein in cereals is well-documented (Simmonds, 1995) and malt barley cultivars with higher grain yield also had lower protein in Alberta (O'Donovan et al., 2011). However, exceptions in the present study occurred for Breton that had low grain yield and low protein in relation to other cultivars and for CDC Coalition that had high grain yield and high protein. Simultaneous high grain yield

and high protein is uncommon and desirable, and CDC Coalition may have genetic benefits in future breeding crosses. O'Donovan et al. (2015) similarly reported the low protein concentration of malt cultivars was usually but not always associated with higher grain yields, with one malt cultivar displaying high grain yield and high protein content. The present study also suggests high yielding feed barley cultivars do not always have low protein concentration.

As expected, two-row cultivars had significantly higher test weight than six-row cultivars by an average of 8%, across all environments (Table 5.12). This result is in agreement with Jedel and Helm (1994b; 1995; 1998) who also reported lower test weight in six-row feed barley cultivars in Alberta. The low test weight of Amisk (60.4 kg hL^{-1}) was above, but near, the 59 kg hL^{-1} threshold for Canada No. 1 Grade Feed, which put it at risk for price discounts for downgrading. In 4 of 14 environments, Amisk was downgraded to Canada No. 2 Grade Feed due to test weight below 59 kg hL^{-1} (data not shown). Low test weight barley required increased dry matter intake per unit weight gain in feedlot steers compared to high test weight barley (Grimson et al., 1987), and increased processing prior to feeding (Mathison, 2000). Two-row cultivars have higher test weight compared to six-row cultivars and continue to be better suited for feed barley end-use.

As expected, cultivars with high starch concentration tended to have relatively lower fiber (ADF and NDF) concentrations (Table 5.12). However, there was a significant negative correlation for starch and NDF concentration (R^2= -0.48, P<0.001) but not for starch and ADF concentration (R^2=0.10; P=0.002). Previous studies have reported negative correlation between starch and both ADF and NDF (Engstrom et al., 1992; Surber et al., 2000). The lack

of negative correlation between the starch and ADF concentration may be attributed to the low starch and relatively low ADF concentration of Muskwa that was not characteristic of other cultivars (Table 5.12). The starch concentration of two-row cultivars was an average of 2% higher than six-row cultivars, and CDC Coalition had the highest starch content. The differences in starch concentration observed between morphological row groups may have been linked to differences in test weight because starch concentration was positively correlated to test weight (R^2= 0.18, *P*<0.001). In Washington and Manitoba, Ovenell-Roy et al. (1998b) and Campbell et al. (1995) also reported higher test weight barley cultivars had higher starch and lower fiber concentrations. The six-row cultivar, Breton, had the highest ADF concentration and the two-row cultivars CDC Coalition and Champion had the lowest (most desirable) ADF concentrations, with other cultivars being intermediate (Table 5.12). The lower ADF concentration of the six-row cultivar, Muskwa, relative to other six-row cultivars, was likely reflective of it's relatively higher test weight (Campbell et al., 1995). In the present study, test weight and ADF had a small, but significant, negative correlation (R^2= -0.10, *P*<0.001), while test weight and NDF were more strongly negatively correlated (R^2= -0.45, *P*<0.001). This agrees with previous reports on the negative relationship between barley test weight and fiber content (Grimson et al., 1987; Yang et al., 2013). As expected, NDF was significantly higher (less desirable) in six-row cultivars compared to two-row cultivars (Table 5.12). The six-row cultivar, Amisk, had an NDF concentration that was 9 to 22% higher than all other cultivars. The average daily gain, carcass weight, and rib-eye size of feedlot steers were lowest when they were fed a six-row barley cultivar with high NDF and low starch content compared to other cultivars (Ovenell-Roy et al., 1998b). The two-row

cultivars CDC Coalition and Champion barley may have superior digestibility in feedlot cattle because barley with lower fiber had increased digestibility (Engstrom et al., 1992).

The more favourable feed to weight gain ratio and animal performance of feedlot steers fed two-row cultivars compared to those fed six-row cultivars was attributed to lower NDF and higher net energy content in two row cultivars (Ovenell-Roy et al., 1998b). The utilization of higher feed quality, two-row barley, may result in improved feedlot animal performance because of higher test weight, higher starch, lower NDF and intermediate to low ADF concentrations. However, because NDF concentration varied widely between cultivars in the present study, and because NDF digestibility and chemical composition has been reported to vary between cultivars and between NDF concentration (Ovenell-Roy et al., 1998a; 1998b), investigation of NDF digestibility in feed barley cultivars grown in Alberta is required to confirm feed quality and animal performance.

5.3.3. Effect of Management

Management significantly affected most agronomic variables but of the quality variables, only NDF was affected (Table 5.10). Advanced management increased NDVI, maturity, grain yield, N yield, and kernel weight (Table 5.10 and 5.11).

The 7.5% NDVI increase in response to advanced management (Table 5.11) was likely influenced by the post-emergence N and dual fungicide application. Numerous Western Canadian studies have reported that fungicides provide green leaf area protection from foliar barley disease (Kutcher and Kirkham, 1997; Kutcher et al., 1999; Kutcher et al., 2011; Turkington et al., 2015; Turkington et al., 2004; Turkington et al., 2012). Leaf disease

assessments revealed standard management (lower NDVI) had greater diseased leaf area than advanced management (higher NDVI) in most environments (Table 5.9). Nilsson and Johnsson (1996) reported spectrometry readings were highly correlated with disease incidence in barley, and Franke (2007) reported 89% accuracy of disease detection using late season NDVI in winter wheat. In Alberta, post-emergence N application (34kg N ha^{-1} with a urease inhibitor) just prior to BBCH 30 increased NDVI slightly by 2% and dual fungicide application increased NDVI by 7% across 14 environments compared to the untreated controls in cv. Amisk feed barley (Chapter 3 and 4).

Management did not affect plant height or lodging (Table 5.10). Clark and Fedak (1977) reported temporary effects of CCC on barley lodging. Previous studies in South Africa and Finland reported that CCC had limited effectiveness on barley, with either no height decrease or a small (2cm) height decrease (Rajala and Peltonen-Sainio, 2008; Ramburan and Greenfield, 2007). Similarly, Chapter 3 reports that CCC resulted in a small 1cm decrease in cv. Amisk barley height and had no effect on lodging in Alberta environments. Conversely, Clark and Fedak (1977) reported variable height decreases between 0 and 10% in the majority of the 53 barley cultivars studied in Eastern Canada. Ours and previous studies show that despite the variable effects of CCC on height, CCC was not effective management tool to decrease lodging in barley.

The grain yield increase for advanced management was consistent across cultivars and ranged narrowly between cultivars from 9 to 11% (data not shown) with an average 9.3% yield increase over all cultivars (Table 5.11). The post-emergence N, CCC, and dual fungicide likely all contributed to the 9.3% yield increase. Baethgen et al. (1995) reported BBCH 30 was

the most yield responsive time for N application in Uruguay malt barley production under conventional tillage and 500-800mm growing season precipitation. Western Canadian studies on post-emergence N application in spring barley are limited. Chapter 4 describes a small 2.4% yield increase from 34 kg ha^{-1} N and a urease inhibitor just prior to BBCH 30 in cv. Amisk spring barley across 14 Alberta environments. Therefore, it is unlikely the advanced management yield increase in the present study was solely from the post-emergence N component of the advanced management treatment. Eastern Canadian studies reported CCC application at BBCH 30 resulted in occasional yield increases up to 10% in 1 of 2 spring barley cultivars from increased kernels main culm $spike^{-1}$ as a result of decreased spikelet primordium abortion (Ma and Smith, 1991b; 1992a). Chapter 3 describes a 2.2% yield increase in cv. Amisk barley when CCC was applied at BBCH 31. Reports of yield increase resulting from foliar fungicide application range between 4 and 37%, with smaller increases occurring when crop rotation was long, when preceding stubble type was a non-barley species, and when cultivars had improved genetic resistance (Kutcher and Kirkham, 1997; Kutcher et al., 1999; 2011; Turkington et al., 2015). Chapter 3 reports a 4.6% yield increase with a dual fungicide application at 355 plants m^{-2} seeding rate compared to no fungicide in cv. Amisk barley. Therefore, the effects of post-emergence N, CCC, and foliar fungicides on grain yield were likely relatively small individually, but collectively resulted in the 9.3% yield increase in the advanced management treatment.

No cultivar x management interaction occurred for grain yield despite variation in genetic disease resistance between cultivars (Table 5.7). The crop rotation on fields where trials were conducted consisted of 2 years of non-barley crop species (canola in the year

prior and a non-barley crop species two years prior) before the trial year in all environments except Lethbridge rainfed in 2014 and Lethbridge irrigated in 2015 where there was 1 year of non-barley species (canola) planted prior to the trial year. Low levels of inoculum and foliar disease in the trial environments, as a result of this rotation history, may have negated differential yield responses between cultivars to the foliar fungicide component of the advanced management treatment. Two overwinter periods were sufficient for sporulation of foliar leaf disease inoculum to decline to low levels in the Saskatchewan Parkland (Duczek et al., 1999). Decreased risk of foliar leaf spot disease was reported when there was at least one year of wheat (*Triticum aestivum* L.), dry pea (*Pisum sativum* L.), or canola grown before barley compared to barley grown directly on barley stubble (Krupinsky et al., 2004; Turkington et al., 2006; Turkington et al., 2012). In Ontario winter wheat production, Brinkman et al. (2014) reported fewer cultivar x foliar fungicide timing interactions for grain yield at locations where disease pressure was low. Therefore, spring barley cultivars may not require differential fungicide management to maximize yield when a long crop rotation (2 or more years between barley plantings) is followed.

Kernel weight had a small but significant 1.5% increase in response to advanced management (Table 5.10 and 5.11). Turkington et al. (2012) similarly reported a 2% increase in kernel weight and <1% increase in test weight with a single foliar fungicide application in malt barley. Reports of kernel weight response to CCC at beginning of stem elongation were more variable. Ma and Smith (1991a) reported kernel weight increases ranging from non-significant to 19% depending on barley cultivar in response to CCC application at BBCH 30 while a study in Finland reported a 6% kernel weight decrease in 1 of 3 years when CCC was

applied at BBCH 30-31 (Rajala and Peltonen-Sainio, 2008). The increase in kernel weight observed in the present study was likely too small to account alone for the 9.3% yield increase in response to advanced management but unmeasured yield components such as kernels m^{-2}, kernels $spike^{-1}$, and spikes m^{-2} likely contributed to the grain yield increase. Kernels m^{-2}, kernels $spike^{-1}$, and spikes m^{-2} were the yield components most increased with post-emergence N applied at BBCH 30 in Uruguay production conditions, with kernel weight being the least responsive (Baethgen et al., 1995).

Advanced management increased N yield by an average of 11 kg N ha^{-1} across environments (Table 5.11). This showed that not all of the 34 kg ha^{-1} post emergence N that was applied just prior to BBCH 30 was recovered in the grain. The urease inhibitor NBPT may have reduced but likely didn't eliminate volatilization by preventing hydrolysis of urea into NH_4^+ (Watson et al., 1994). Chapter 4 reported NBPT amended UAN increased barley grain N yield compared to UAN alone in just 1 of 14 environments. The nitrate component in UAN is susceptible to loss through leeching and denitrification (Grant and Wu, 2008), and this may have been an avenue for loss of post-emergence N in the present study. Additionally, low moisture conditions in some environments may have reduced plant uptake of post-emergence N. The observed increase in N yield resulted from increased grain yield and not increased grain protein because of the small effect of management on protein (Table 5.12). The effect of management on grain protein was nearly significant (P=0.056) and a small numerical increase in protein of 0.1% was observed with advanced management (Table 5.12). A small linear protein increase also occurred for post-emergence N rates between 0 and 68 kg ha^{-1} applied just prior to BBCH 30 in Alberta (Chapter 4). The small protein

response in the study was expected because post-emergence N increased protein is more typical when post-emergence N is applied after anthesis (Bly and Woodard, 2003).

Advanced management did not significantly affect test weight, but there was a significant cultivar x management interaction for test weight (Table 5.10). Compared to standard management, advanced management significantly increased the test weight of six-row Amisk by 0.8 kg hL^{-1} (P=0.027) and two-row Busby by 1.1 kg hL^{-1} (P=0.002), while management had no significant effect on the other cultivars (data not shown). Advanced management may assist Amisk to achieve Canada No. 1 Feed Grade in situations where test weight was near 59 kg hL^{-1}, but it was notable that advanced management increased the test weight of Amisk above 59 kg hL^{-1} in only one of the four environments where Amisk was downgraded to Canada No. 2 Feed due to low test weight (data not shown).

Although management did not affect starch concentration, there was a trend (P=0.056) towards a significant interaction between cultivar and management (Table 5.10). The interaction was caused by Champion having a significantly higher (P=0.001) advanced management starch concentration of 61.4% compared to the lower standard management starch concentration of 61.1%, while other cultivars had no significant increase in starch concentration with advanced management (data not shown). In contrast, Chapter 4 describes a linear starch decrease with increasing post-emergence N rate in cv. Amisk feed barley. These contrasting results suggest cultivar specific starch concentration responses to post-emergence N. In a Swedish study, barley grain starch concentration of 10 cultivars decreased from 61% to 57% with increasing spring N rate (45, 90, 135 kg N ha^{-1}) (Oscarsson et al., 1998). The decrease in starch concentration reported by Oscarsson et al. (1998) was

accompanied by increased yield and kernel number, and starch dilution as a result of increased kernels plant^{-1}. Importantly, Oscarsson et al. (1998) reported a cultivar x N rate interaction from differences in magnitude decreases in starch content between cultivars.

Acid detergent fiber was unaffected by advanced management (Table 5.10 and 5.12). Similarly, post-emergence N rates between 0 and 68 kg ha^{-1} did not affect ADF concentration (Chapter 4), and foliar fungicides did not effect ADF concentration in cv. Amisk barley (Chapter 3). Conversely, NDF concentration was lowered by 1.2% (0.2% absolute NDF) for advanced compared to standard management (Table 5.12). There was also a significant interaction between cultivar and management for NDF (Table 5.10). All cultivars had significantly lower NDF with advanced management compared to standard management, but the magnitude decrease for Champion, 0.34% absolute NDF, was greater than the absolute NDF decrease of other cultivars that ranged between 0.13% and 0.27% (data not shown). These small NDF decreases were likely not biologically significant. However, the decreased fiber and increased starch of Champion under advanced management demonstrates the negative relationship reported between starch and ADF by Engstrom et al. (1992).

5.3.4. Effect of environment on treatment response

Cultivar performance depended on environmental conditions for all variables except lodging, as indicated by the large proportion (≥10%) or significance (P<0.01) of the environment x cultivar (E x C) variance estimate (Table 5.10). The grain yield and N yield responses to management depended on the environment (Table 5.10). Conversely, cultivar response to management was consistent across environments for all variables measured, as

indicated by the small and non-significant environment x C x M (E x C x M) variance estimates (Table 5.10). Consistently low disease pressure in all environments, which did not exceed 19% diseased leaf area for standard management (Table 5.9), was likely an important factor influencing the lack of E x C x M interactions observed. In 338 Alberta commercial barley fields surveyed between 1995 and 1997, the severity of net blotch and scald ranged between 0 and 54 % leaf area diseased (PLAD), and the average severities of 5 and 2 PLAD of net blotch and scald, respectively, were reflective of the low disease levels encountered in the present study (Turkington et al., 2006). Similarly, in central Alberta in 2013, net form net blotch and scald severity in 19 surveyed fields ranged from 0 to 12 PLAD, also representative of the low disease levels encountered in the present study (Rauhala and Turkington, 2014). This indicates that the low disease levels encountered in the study were typical of those found in Alberta fields.

Biplot analysis comparing mean and coefficient of variation (CV) of cultivar and management (Figure 5.2) was used to visualize the response magnitudes and variability across environments (Francis and Kannenberg, 1978).

Biplot analysis indicated cultivar height was variable across environments (Figure 5.2a). The intermediate height cultivars Xena and Champion had the least variability across environments compared to other cultivars. The cultivar coefficients of variation were larger for NDVI than those of height, meaning that overall cultivar NDVI variability across environments was higher (Figure 5.2b). CDC Austenson, Vivar, and Champion had high NDVI and low variability, whereas Amisk and Gadsby had relatively high NDVI but also high variability across environments. Conversely, the NDVI of Xena was low but highly variable

and the NDVI of the six-row cultivars Muskwa and Breton was consistently low. The overall variability of cultivar maturity was low in relation to both height and NDVI (Figure 5.2c). The majority of cultivars had short maturity with low variability, although variability increased with increasing maturity (Figure 5.2c). Gadsby, CDC Austenson, and Amisk were the longest maturing cultivars and had higher variability across environments.

The biplot for grain yield showed high variation of cultivar yields across environments (Figure 5.3a), likely resulting from the diverse levels of growing season precipitation observed across environments (Table 5.1). The yield stability of cultivars generally decreased as yield increased; that is to say, high yielding cultivars had less yield predictability across environments than low yielding cultivars. Champion was the only cultivar with high yield and low variability, meaning it had a production advantage of being more consistently high yielding across environmental conditions (Figure 5.3a). Champion maintained higher yields compared to other cultivars in low precipitation environments (Falher 2014, Falher 2015, and Lethbridge Rainfed 2015) (data not shown). In the driest environment of the study, Falher 2014, Champion yielded 6.9% higher than the next highest yielding cultivar, Xena (data not shown). Therefore, Champion demonstrated significant yield advantages and risk mitigation under moisture-limited conditions and should be selected in rainfed environments where low precipitation is expected or historically normal. The consistently low yield of Gadsby, Busby, and Muskwa across environments placed these cultivars at a disadvantage from a yield expectation perspective. Amisk had the highest yield variability between environments that was not consistently linked to precipitation level. Amisk was among the lowest yielding cultivars in 10 environments, but at Bon Accord 2014, Lethbridge irrigated 2014 and 2015,

and Killam 2016, it was among the highest yielding cultivars (data not shown). The environments where Amisk was higher yielding represented both a low precipitation environment (Bon Accord 2014) and high precipitation environments (Lethbridge irrigated 2014 and 2015, and Killam 2016). Additionally, in the highest precipitation environment, Lethbridge irrigated 2016, Amisk was among the lowest yielding cultivars (data not shown). The unpredictability of cv. Amisk yield presented a disadvantage from a risk perspective. The biplot analysis also showed that the grain yield of CDC Austenson was relatively variable, although similar to that of Xena, CDC Coalition, and Vivar. CDC Austenson was among the highest yielding cultivars in all environments (12) except in the dry conditions encountered at Falher 2014 and 2015, where it was intermediate yielding (data not shown). Notably, in the dry environment of Lethbridge rainfed 2015, CDC Austenson was among the highest yielding cultivars (data not shown). Therefore, although CDC Austenson yield was the 2nd most variable in the study (Figure 5.3a), the high yields observed with this cultivar negated some of the production risk associated with the occasional intermediate yield performance in two dry environments. Champion should be grown in low precipitation environments, and CDC Austenson, Xena, or CDC Coalition should be grown in average or above average precipitation or irrigated environments to achieve maximum grain yield. The variability of N yield across environments for most cultivars followed similar trends to the variability of cultivar grain yield across environments (Figure 5.3b).

Similar to cultivar yield variability, yield variability in response to management also increased as yield increased. The higher grain yield of advanced management was more variable than the lower yielding standard management (Figure 5.3a). The higher variability

observed with advanced management was related to growing season moisture supply, and advanced management yield increases were larger when growing season precipitation was higher. Yield increases from advanced management were often small (1-3%) and not significant where growing season precipitation was limiting (Bon Accord 2015, Falher 2014, and Falher 2015) but where moisture supply was close to or above the long-term average, between 251 and 502mm (Bon Accord 2016, Killam 2016, Lethbridge rainfed 2014 and 2016, and Lethbridge irrigated 2014, 2015, and 2016), yield increases were greater, between 8 and 18% (data not shown). An exception was Falher in 2016 where growing season precipitation was slightly above the long-term average but only relatively small (2%) yield increases occurred with advanced management. Lethbridge rainfed 2015 had relatively large (5.8%) yield response to advanced management (data not shown) despite the low growing season precipitation. The relatively large yield increase in response to advanced management in this dry environment may be explained by the prevalence of stripe rust (*Puccinia striiformis* Westend. *spp*.) at this site (Table 5.9). Grabow (2016) reported temperatures between 5 and 25°C and relative humidity above 87% were strongly correlated with stripe rust infection in Kansas winter wheat, while precipitation factors less useful predictors for epidemics. Western Canadian studies have reported that barley grain yield response to N applied at seeding was larger in magnitude when growing season precipitation was adequate or high (Grant et al., 1991b; McKenzie et al., 2004b). Our results indicate that grain yield response to advanced management that includes N applied just prior to BBCH 30 is also dependent on growing season precipitation. Increased response to foliar fungicide application under adequate or high moisture conditions likely also contributed to the larger grain yield

increases observed for advanced management in environments with higher precipitation, as was reported by Kutcher et al. (2011). Therefore, advanced management practices should be applied only in environments where above-average growing season precipitation (between 251- 502mm) is observed or expected, and these management decisions can be made in-season, prior to treatment application.

The N yield variability for management was slightly lower than the yield variability for management across environments (Figure 5.3b). The probable cause was the increased protein in drier environments supplying more grain N and compensating for the lower amount of N supplied by the reduced grain yields in dry environments (data not shown).

Kernel weight and test weight each had large (>10) and significant ($p<0.01$) ExC variance estimates (Table 5.10). The biplot analysis revealed relatively high kernel weight and high variability across environments for two-row cultivars compared to six-row cultivars (Figure 5.4a). The notable exception was the six-row cultivar Muskwa that had low kernel weight with high variability. The greater variability of Muskwa kernel weight was caused by higher kernel weights than other six-row cultivars, comparable to two-row cultivars, in the dry environment of Falher 2014 (data not shown). In the other low precipitation environments, Muskwa did not follow this trend and had kernel weights similar or lower than other six-row cultivars (data not shown). The six-row cultivars Amisk, Vivar, and Breton had consistently low kernel weight across environments. Similar to kernel weight, two row cultivars had higher test weight than six-row cultivars, but opposite to kernel weight, the test weight stability of two-row cultivars and the six-row Muskwa was higher than other six-row cultivars across environments (Figure 5.4b). The high variability in the test weight of the six-row

cultivars Amisk, Breton, and Vivar was a result of more greatly reduced test weight under low precipitation environments, with less than 200 mm of precipitation, relative to two-row cultivars (data not shown). For example, at Falher 2015 (151mm precipitation), two-row cultivar test weight was 19% higher than six-row cultivar test weight (data not shown). The low test weights of the six-row cultivars Amisk, Breton, and Vivar were near the threshold of 59 kg hL^{-1} for Canada No. 1 Grade feed barley, and the high variability in test weight put these cultivars at increased risk for downgrading (Figure 5.4b). The six-row Amisk was below the minimum test weight requirement of 59 kg hl^{-1} to meet Canada No. 1 Grade feed barley in four of 14 environments, and in three of 14 environments the test weights of the six-row cultivars Breton and Vivar were also below the minimum requirement (data not shown). Therefore, two-row cultivar test weight quality was superior to that of the six-row cultivars based on both magnitude and risk perspectives, especially in low precipitation environments.

The cultivar coefficients of variation were higher for grain protein concentration than for the other quality constituents (starch, ADF, NDF); that is to say, grain protein was more variable across environments than other grain quality constituents (Figure 5.5a). Therrien et al. (1994) also reported that environment had a large effect on protein. Patterns between cultivar mean and CV were less apparent in the protein, starch, ADF, and NDF biplots (Figure 5.5) compared to the agronomic and yield biplots (Figure 5.2 and 5.3). However, the biplot analysis revealed Gadsby, Amisk, and Busby had consistently high protein, whereas CDC Coalition had high protein with greater variability, and Champion had lower protein with greater variability (Figure 5.5a). The low protein of CDC Coalition at Lethbridge rainfed 2014 caused the increased protein variability for this cultivar (data not shown). Growers could

select Amisk, Gadsby, or Busby to achieve the highest and most consistent protein, however because these cultivars had significantly lower grain yield than the two-row CDC Coalition that also had high protein in most environments, CDC Coalition is a more viable choice.

Cultivar starch content had lower variability compared to all other response variable biplots, as indicated by the overall small range of CV in the biplot (Figure 5.5b). Although statistically significant, the effect of environment on starch concentration in the present study may have been relatively low and not agronomically or biologically significant because of the absence of sustained temperature extremes in the study (data not shown). Savin and Nicolas (1996) reported periods of drought or heat stress (40°C for 6 h day^{-1}) sustained for 5 or 10 days post-anthesis reduced starch accumulation in malt barley grain.

The cultivar coefficients of variation were alike for ADF and NDF, meaning that ADF and NDF variability across environments was similar (Figure 5.5c, 5.5d). The ADF content of Vivar, CDC Austenson, and Xena was above average with low variability, while Breton had the highest ADF and variability across environments (Figure 5.5c). The ADF variability of Breton was caused by intermediate and low ADF at Lethbridge irrigated and rainfed sites in 2014, respectively, in contrast with the highest ADF in all other environments (data not shown). CDC Coalition, Muskwa, and Gadsby had desirably low ADF that was relatively less variable across environments and from a magnitude ADF and risk perspective these cultivars were favourable.

The high NDF of Amisk was intermediately stable across environments and Gadsby and Champion had low NDF and low variability (Figure 5.5d). Muskwa had the least, and Xena and CDC Coalition had the most variability in NDF across environments. This variability

was a result of the high NDF of Xena at Lethbridge rainfed 2014 in contrast with intermediate NDF elsewhere, and the intermediate NDF of CDC Coalition at the same location, in contrast with low NDF elsewhere (data not shown). Despite the NDF variability of these cultivars, Amisk had the highest NDF across all environments, and the magnitude of NDF overshadowed the importance of variation in other lower NDF cultivars across environments.

5.4. Conclusion

The lack of yield increase, and often, the presence of yield declines, in new feed barley cultivars (2008-2013 registration) compared to older cultivars (2000 registration) presents a serious obstacle for feed barley yield increases and retention of barley in the Alberta crop rotation. However, the highest yielding cultivars from the two-row class (CDC Austenson, Xena, CDC Coalition, and Champion) should be grown to maximize yield with the current feed barley genetics available. Recently registered six-row cultivars and the two-row cultivars Gadsby and Busby were among the lowest yielding cultivars.

The two-row cultivar, Champion, was the highest yielding cultivar in low precipitation environments, having up to 6.9% higher yield than the 2nd highest yielding cultivar in dry conditions. Champion can be grown to reduce production risk caused by low precipitation. Gadsby (two-row), Muskwa (six-row), and Busby (two-row) were low yielding regardless of environment, and are therefore not recommended to growers. The unstable grain yield of Amisk across environments represented increased production risk and again is not recommended to growers. The higher yielding and more stable two-row cultivars: CDC Austenson, Xena, CDC Coalition, and Champion, or the six-row cultivar Vivar are favourable

choices for growers due to their greater yield and yield stability across diverse growing environments.

Of the cultivars tested, the two-row cultivar CDC Coalition had the least lodging, was among the highest yielding, and had desirable quality characteristics. Two-row cultivars had 8% higher test weight than six-row cultivars averaged across environments, and in environments with less than 200mm of precipitation, this difference increased to up to 19%, and downgrading to Canada No. 2 Feed Grade occurred for the six-row cultivars Amisk, Breton, and Vivar. In addition, two-row cultivars had desirably higher starch concentration, lower NDF concentration, and generally intermediate to lower ADF concentration compared to six-row cultivars. To avoid price discounts and reduced feedlot animal performance in the end-use market, six-row cultivars should not be grown in Alberta, particularly in rainfed environments.

The 9.3% yield increase observed from advanced management was nearly 3 times larger than the greatest genetic yield advance observed for the highest yielding recently registered cultivar, CDC Austenson, compared to the older cultivars: Xena and Vivar. In average or above average precipitation and irrigated environments (251 to 502mm), advanced management increased grain yield by 8 to 18% compared to standard management, whereas the increase was much smaller, 1 to 3%, in environments that received below average precipitation (101 to 181mm). In-season decisions for advanced management applications based on precipitation levels are required to maximize input use efficiency and grain yield.

Standability was not improved with advanced management, and genetic lodging resistance was the most effective tool available to growers to prevent lodging. CDC Coalition had the least lodging of the 10 cultivars tested and it should be grown to achieve the greatest standability. A pre-plant agronomic decision to select a cultivar with genetic lodging resistance is currently required to manage barley lodging. Advanced management increased NDVI and kernel weight but the effect on quality parameters was small or not of agronomic or biological significance. Therefore, cultivar selection was a more effective tool overall for achieving higher quality based on test weight, starch, ADF, and NDF content. Advanced management did not correct low test weight in six-row cultivars, and therefore growing six-row barley cultivars presented an increased risk of low quality, especially in rain-fed environments. Any of the two-row cultivars tested (CDC Austenson, CDC Coalition, Champion, Xena, Busby, or Gadsby) should be grown to achieve highest feed quality.

Cultivar specific response to advanced management occurred for maturity and test weight, however, the differences were small. The low disease pressure encountered in study environments likely influenced the lack of cultivar-specific yield response to advanced management. The preceding crop rotation in the study environments was reflective of the average provincial barley rotation in Alberta, where only 7% of 223 surveyed fields grew barley frequently (3 times in 4 years or 4 times in 4 years) between 2007-2010, and where 58% of fields that did grow barley grew it infrequently; just once every 4 years (personal communication, Julia Leeson, 2017). Therefore, feed barley cultivars should usually not require differential management targeting yield and agronomic responses under the predominant longer rotations in Alberta (barley once in 4 years) that encourage low disease

pressure in field environments. However, it is possible that environments with high disease pressure, which did not occur in this study and occurred infrequently in Alberta, may require differential management of cultivars with diverse levels of genetic disease resistance.

CDC Austenson, Xena, CDC Coalition, Champion, and Vivar were the highest yielding cultivars in the study. CDC Austenson, Xena, and CDC Coalition were the top 3 highest yielding cultivars, although not statistically different than Vivar and Champion. However, the six-row Vivar had low test weight (as did all of the lower yielding six-row cultivars in the study: Amisk, Breton, and Muskwa), especially in dry environments, that presented a quality risk, so growing the two row cultivars CDC Austenson, Xena, and CDC Coalition is required for high yield and grain quality in average or above average (irrigated) precipitation environments. In dry environments with below average precipitation, the two-row cultivar, Champion, should be grown to mitigate the risk of yield loss from drought, as it was the highest yielding, nearly 7% higher than the next highest yielding cultivar, in precipitation limited conditions. CDC Coalition had the greatest standability and presented an avenue for growers to simultaneously achieve high yield, high quality, and lower lodging in environments with average or above average precipitation. CDC Austenson had intermediate lodging, whereas Xena and Champion had higher lodging severity and therefore Xena and Champion should not be grown in high precipitation environments with elevated lodging risk. Because lodging risk is smaller in the low precipitation environments where Champion out-yielded other cultivars, Champion remains a viable option to mitigate the risk of yield loss caused by drought despite the elevated tendency to lodge in relation to CDC Coalition and CDC Austenson.

To achieve the highest grain yield, grain quality, and intermediate to excellent standability in environments with average or above average precipitation or irrigation, advanced management should be used on CDC Austenson or CDC Coalition to achieve yield increases between 8 and 18%, but not in environments with below average precipitation, where negligible yield increases between 1 and 3% resulted for all cultivars. CDC Coalition with advanced management is recommended to achieve simultaneous high grain yield, high grain quality, and excellent standability of the 10 cultivars tested. Although Champion had the highest yield in dry environments, advanced management is not recommended on Champion in low precipitation rainfed environments, because negligible yield increases occurred under precipitation limited conditions.

Table 5-1. Soil classification, seeding date, harvest date, growing season precipitation, and site coordinates for each environment (site-year).

Site	Year	Coordinates	Soil classification	Seeding date	Harvest date	Observed precipitation (mm)[Z]	Long-term mean precipitation (mm)[Y]
Bon Accord	2014	53°48'N 113°28'W	Black Chernozem	9 May	4 Sept	181	344
Rainfed	2015	53°48'N 113°27'W	Black Chernozem	27 April	31 Aug	121	
	2016	53°55'N 113°27'W	Black Chernozem	28 April	8 Sept	323	
Falher	2014	55°48'N 117°11'W	Gray Luvisol	22 May	30 Aug	101	301
Rainfed	2015	55°47'N 117°10'W	Gray Luvisol	14 May	3 Sept	155	
	2016	55°40'N 117°2' W	Gray Luvisol	10 May	15 Sept	338	
Killam	2014	52°48'N 111°52'W	Black Chernozem	24 May	25 Aug	263	309
Rainfed	2016	52°51'N 111°53'W	Black Chernozem	16 May	14 Sept	345	
Lethbridge	2014	49°22'N 112°55'W	Dark Brown Chernozem	1 May	16 Sept	426	317
Irrigated	2015	49°41'N 112°39'W	Dark Brown Chernozem	24 April	12 Aug	282	
	2016	49°42'N 112°31'W	Dark Brown Chernozem	11 April	17 Aug	502	
Lethbridge	2014	50°33'N 113°53'W	Black Chernozem	16 May	17 Sept	326	305
Rainfed	2015	49°22'N 112°55'W	Dark Brown Chernozem	17 April	5 Aug	116	
	2016	49°40'N 112°31'W	Dark Brown Chernozem	13 April	16 Aug	251	

[Z]Observed precipitation from seeding to harvest. This includes precipitation and irrigation at Lethbridge Irrigated site.
[Y]Calculated from April 1 to Sept 15 using 30 year historical data interpolated from the nearest geographical provincial weather station (Alberta Agriculture and Forestry, 2016).

Table 5-2. Soil descriptions and nutrient properties before fertilizer application at two sample depths for each site-year.

		Soil properties													
		pH		CEC (cmol kg^{-}1)[Z]		OM (%)[Y]		NO_3–N[X]		P[W]		K[V]		S[U]	
								(mg kg^{-1})							
Site	Year	Sample Depth (cm)[T]													
		0-15	16-30	0-15	16-30	0-15	16-30	0-15	16-30	0-15	16-30	0-15	16-30	0-15	16-30
Bon Accord	2014	6.3	6.9	23.2	22.5	9.6	5.0	10	16	21	19	167	107	32	118
Rainfed	2015	5.4	6.4	26.4	23.5	8.7	6.3	9	1	24	12	218	129	16	11
	2016	5.1	5.8	26.6	17.5	7.0	5.6	20	5	18	16	107	89	23	15
Falher	2014	6.1	6.9	13.2	19.1	4.8	2.3	10	10	24	-	226	176	15	14
Rainfed	2015	5.7	6.2	9.1	14.8	2.7	2.4	20	17	17	0	106	96	10	12
	2016	5.6	5.8	17.1	22.8	5.3	3.1	11	8	30	8	244	114	16	14
Killam	2014	5.1	6.0	15.1	10.6	4.5	2.4	11	8	48	20	261	112	18	16
Rainfed	2016	5.3	5.6	16.9	17.8	5.2	3.0	12	5	37	20	228	104	19	13
Lethbridge	2014	7.9	8.1	35.2	39.8	4.2	2.7	8	26	9	5	251	265	11	25
Irrigated	2015	7.5	7.8	31.8	40.4	3.8	3.1	13	26	39	14	330	299	18	40
	2016	7.2	7.7	28.9	34.1	3.4	2.7	18	16	31	14	345	379	17	47
Lethbridge	2014	6.9	7.5	24.8	37.8	4.2	2.7	1	2	15	6	348	262	16	29
Rainfed	2015	7.7	7.8	43.3	44.5	3.9	2.9	6	9	7	2	350	303	8	21
	2016	6.9	7.7	24.5	34.0	3.0	2.2	7	7	16	11	385	376	26	95

[Z]Cation exchange capacity
[Y]Soil organic matter
[X]Nitrate nitrogen
[W]Phosphorus (bray)
[V]Potassium
[U]Sulfur
[T]0-15cm and 15-60cm for NO_3, P, K, and S at Lethbridge irrigated and rainfed sites.

Table 5-3. Seeding equipment and plot area information for each site-year.

Site	Year	Seed Drill Type	Opener Type	Fertilizer Placement	Row Spacing	Number of Rows	Seeded Plot area
					---m---		----m^{-2}---
Bon Accord	2014	Air seeder	Atom Jet hoe	Side band[Z]	0.20	8	10.9
Rainfed	2015	No-till box seeder	Double disc	Mid-row band[Y]	0.25	6	10.2
	2016	No-till box seeder	Double disc	Mid-row band	0.25	6	10.2
Falher	2014	No-till box seeder	Double shoot hoe	Side band	0.23	6	11.7
Rainfed	2015	Air seeder	Double shoot hoe	Side band	0.23	6	11.7
	2016	Air seeder	Double shoot hoe	Side band	0.23	6	11.7
Killam	2014	Air seeder	Atom Jet hoe	Side band	0.20	8	10.9
Rainfed	2015	No-till box seeder	Double disc	Mid-row band	0.25	6	10.2
	2016	No-till box seeder	Double disc	Mid-row band	0.25	6	10.2
Lethbridge	2014	No-till box seeder	John Deere 90 series disc	Side band	0.25	8	20.0
Irrigated	2015	No-till box seeder	John Deere 90 series disc	Side band	0.25	8	20.0
	2016	No-till box seeder	John Deere 90 series disc	Side band	0.25	8	20.0
Lethbridge	2014	No-till box seeder	John Deere 90 series disc	Side band	0.25	8	20.0
Rainfed	2015	No-till box seeder	John Deere 90 series disc	Side band	0.25	8	20.0
	2016	No-till box seeder	John Deere 90 series disc	Side band	0.25	8	20.0

[Z]Side banding placed fertilizer 5cm to the side and 2cm below the seed
[Y]Mid-row banding placed fertilizer 12.5cm to the side and 4cm below the seed

Table 5-4. Yield targets and fertilization rates of N, P, K, and S applied at seeding for each environment.

			Nutrient Applied			
Site	Year	Yield Target[Z]	N[Y]	P_2O_5[X]	K_2O[W]	S[V]
		---MT ha^{-1}---	----------Kg ha^{-1}----------			
Bon Accord	2014	4.8	88	50	22	17
Rainfed[U]	2015	4.8	120	50	22	0
	2016	4.8	102	34	67	5.5
Falher	2014	4.5	108	56	22	22
Rainfed	2015	4.5	90	34	28	28
	2016	4.5	68	39	22	17
Killam	2014	5.6	130	22	22	5
Rainfed	2015	5.6	133	45	22	11
	2016	5.6	161	17	22	6
Lethbridge	2014	6.3	123	55	0	0
Irrigated	2015	5.5	66	30	0	0
	2016	5.5	81	35	0	0
Lethbridge	2014	3.8	95	25	0	0
Rainfed	2015	3.8	75	45	0	0
	2016	3.8	77	35	0	0

[Z]Yield goals are based on the land cooperator's 10-year on-farm feed barley yield average in each environment
[Y]Nitrogen
[X]Phosphorus
[W]Potassium
[V]Sulfur
[U]Co-operator had no record of feed barley yield and so their long term malt barley yield average was adjusted for the differential between the AFSC (Agriculture Financial Services Corporation, 2014) Risk Area yield average for feed and malt barley.

Table 5-5. Pre-emergence and in-crop herbicide active ingredients, application dates, and application rates for weed control in each site-year.

Site	Year	Pre-emergence weed control		In-crop weed control	
		Active ingredients	Application date	Active ingredients	Application date
Bon Accord	2014	Glyphosate[Z], saflufenacil[Y]	13 May	Florasulam[X], fluroxypyr[W], MCPA ester[V], pinoxaden[U]	11 June
Rainfed	2015	Glyphosate, saflufenacil	4 May	Florasulam, fluroxypyr, MCPA ester, pinoxaden	5 June
	2016	Glyphosate, saflufenacil	4 May	Florasulam, fluroxypyr, MCPA ester, pinoxaden	31 May
Falher	2014	Glyphosate, saflufenacil	21 May	Fluroxypyr, clopyralid, pinoxaden	14 June
Rainfed	2015	Glyphosate	6 May	Florasulam, fluroxypyr, MCPA ester, pinoxaden	8 June
	2016	Glyphosate, tribenuron-methyl[T]	2 May	Florasulam, fluroxypyr, MCPA ester, pinoxaden	5 June
Killam	2014	Glyphosate, tribenuron-methyl	23 May	Florasulam, fluroxypyr, MCPA ester, pinoxaden	12 June
Rainfed	2016	Glyphosate, saflufenacil	13 May	Florasulam, fluroxypyr, MCPA ester, pinoxaden	18 June
Lethbridge	2014	Glyphosate, saflufenacil	28 April	Florasulam, MCPA ester, pinoxaden	6 June
Irrigated	2015	Glyphosate, saflufenacil	21 April	Florasulam, MCPA ester, pinoxaden	27 May
	2016	Glyphosate, saflufenacil	8 April	Florasulam, MCPA ester, pinoxaden	16 May
Lethbridge	2014	Glyphosate, saflufenacil	13 May	Florasulam, MCPA ester, pinoxaden	23 June
Rainfed	2015	Glyphosate, saflufenacil	15 April	Florasulam, MCPA ester, pinoxaden	25 May
	2016	Glyphosate, saflufenacil	18 April	Florasulam, MCPA ester, pinoxaden	25 May

[Z]Glyphosate applied at 360 g ae ha^{-1} rate
[Y]Saflufenacil applied at 18 g ae ha^{-1} rate
[X]Florasulam applied at 2.5 g ae ha^{-1} rate
[W]Fluroxypyr applied at 99 g ae ha^{-1} rate at all site-years except Falher 2014 where it was applied at 140 g ae ha^{-1} rate
[V]MCPA ester applied at 356 g ae ha^{-1} rate
[U]Pinoxaden applied at 61 g ae ha^{-1} rate
[T]Tribenuron-methyl applied at 7.4 g ae ha^{-1} rate

Table 5-6. Insecticide active ingredient, application rate, and application date at site-years requiring insect pest control in the trial area.

Site	Year	Insect controlled	Active ingredient applied	Application rate	Application date
				-----g ae ha^{-1}-----	
Bon Accord	2015	*Melanoplus* spp.	Chlorpyrifos[Z]	396	15 June
Bon Accord	2016	*Oulema melanopus* L.	Malathion[Y]	556	23 June
Bon Accord	2016	*Melanoplus* spp.	Chlorpyrifos	396	18 July
Falher	2016	*Euxoa* spp.	Chlorpyrifos	117	14 June

[Z] (*O, O*-diethyl *O*-3,5,6-trichloro-2-pyridinyl phosphorothioate)

[Y] 2-[(dimethoxyphosphorothioyl)sulfanyl]butanedioate

Table 5-7. Information for barley morphology class, registration year, breeding program, and agronomic characteristics of the feed barley cultivars tested in trials.

					Disease Resistance[Z]					
Cultivar	Class	Year of registration	Breeding program	Grain yield potential (%)[Y]	Scald	Spot blotch	Net-form net blotch	Spot-form net blotch	Height (cm)	Lodging rating[X]
Amisk	6 row feed	2013	AF[W]	106	I	MR	S	I	74	VG
Breton	6 row feed	2012	AF	107	I	MR	I	MR	81	F
Muskwa	6 row feed	2011	AF	105	MR	I	MS	MR	73	G
Gadsby	2 row feed	2010	AF	112	R	S	MS	MR	83	F
Busby	2 row feed	2008	AF	104	I	MR	MS	MR	78	G
CDC Austenson	2 row feed	2008	U of S[V]	112	S	MR	MS	R	78	G
Champion	2 row feed	2007	WestBred LLC[U]	113	S	MS	S	I	77	G
CDC Coalition	2 row feed	2006	U of S	110	S	I	S	MR	74	G
Vivar	6 row feed	2000	AF	109	I	XX	R	MR	74	VG
Xena	2 row feed	2000	Monsanto[T]	112	S	S	S	I	78	G

[Z]S= Susceptible; MS= moderately susceptible; I= intermediate; MR= moderately resistant; R= resistant; XX=insufficient data to describe (Alberta Agriculture and Forestry, 2016a).
[Y]Displayed as percent of AC Metcalfe check variety yield (Alberta Agriculture and Forestry, 2016a).
[X]VG indicates very good, G indicates good, and F indicates fair (Alberta Agriculture and Forestry, 2016a).
[W]Alberta Agriculture and Forestry, Field Crop Development Center. Lacombe, AB, Canada
[V]University of Saskatchewan, Crop Development Center. Saskatoon, SK, Canada
[U]Highland Specialty Grains, Washington, United States
[T]Western Plant Breeders, Montana, United States.

Table 5-8. Plant growth stage, application rate, and application date of inputs applied for the advanced management treatment in each environment.

		Agronomic practice and product rate			
		In-season nitrogen[Z]	Plant growth regulator[Y]	Flag fungicide[X]	Late fungicide[W]
		Plant growth stage for application[V]			
Location	Year	Pre-BBCH 30	BBCH 31-33	BBCH 39	2 wks after BBCH 39
		----------Date applied----------			
Bon Accord	2014	13 June	18 June	2 July	15 July
	2015	9 June	13 June	26 June	10 July
	2016	8 June	10 June	23 June	7 July
Falher	2014	21 June	27 June	4 July	16 July
	2015	15 + 16 June	18 June	6 July	13 July
	2016	21 June	22 June	28 June	13 July
Killam	2014	22 June	26 June	4 July	16 July
	2016	21 June	24 June	5 July	21 July
Lethbridge	2014	12 June	13 June	2 July	10 July
Irrigated	2015	2 June	5 June	19 June	2 July
	2016	31 May	1 June	13 June	28 June
Lethbridge	2014	23 June	25 June	11 July	22 July
Rainfed	2015	4 June	9 June	18 June	2 July
	2016	1 June	1 June	23 June	6 July

[Z]Urea ammonium nitrate (28-0-0) at 34 kg N ha^{-1} rate + the urease inhibitor N-(n-butyl) thiophosphoric triamide formulated as Agrotain at 476 ml ha^{-1} rate

[Y]Chlormequat chloride (2-chloroethyl-trimethyl-ammonium chloride), formulated as Manipulator (Taminco US Inc., 2015) at 1.43 kg ai ha^{-1} rate

[X]Pyraclostrobin (carbamic acid, [2,[[[1-(4-chlorophenyl)-1H-pyrazol-3yl]oxy]methyl]phenyl] methoxy-methyl ester) + metconazole (5-[(4-chlorophenyl)methyl]-2,2-dimethyl-1-(1H-1,24-triazol-1-ylmethyl) cyclopentanol) formulated as Twlinline (Bayer CropScience, Research Triangle Park, NC) at 499 ml ha^{-1} rate

[W]Prothioconazole (2-[2-(1-chlorocyclopropyl)-3-(2-chlorophenyl)-2-hydroxypropyl]-1,2-dihydro-3H-1,2,4-triazole-3-thione) + tebuconazole ([1-(4-chlorophenyl)-4,4-dimethyl-3-(1,2,4,j-triazol-1-ylmethyl)pentan-3-ol]-tetrafluoroetho) formulated as Prosaro (Bayer CropScience, Research Triangle Park, NC) at 790 ml ha^{-1} rate

[V]BBCH growth stage scale (Lancashire et al., 1991)

Table 5-9. Diseases present and average percent fungal diseased leaf area on the flag and flag-1 leaves for advanced and standard management treatments in 14 environments. Leaves were collected from treatments in one replicate in each environment.

		Leaf area diseased (%)[Z]		
		Management		Fungal diseases
Site	Year	Standard	Advanced	present[Y]
Bon Accord	2014	n/a[X]	n/a	NF, SF
Rainfed	2015	1	1	SB, SR
	2016	11	5	NF, SF, SB, SR
Falher Rainfed	2014	n/a	n/a	none
	2015	1	1	SF
	2016	10	9	NF, SB, SR
Killam Rainfed	2014	n/a	n/a	SC, NF, SF
	2016	19	9	SC, NF, SF, SR
Lethbridge	2014	n/a	n/a	NF, SF
Irrigated	2015	4	1	NF, SR
	2016	10	5	NF, SF, SB, SR, PM
Lethbridge	2014	n/a	n/a	NF, SF
Rainfed	2015	12	7	SR, NF, SF
	2016	9	6	NF, SF, SR

[Z]Average total diseased area of 5 flag and 5 penultimate leaves per treatment. Recorded in 2015 and 2016 only

[Y]NF= net-form net blotch, SF= spot-spot form net blotch, SB=spot blotch, SC= scald, SR= stripe rust (*Puccinia striiformis spp*), PM= powdery mildew

[X]Information not collected in 2014

Table 5-10. *P* values and variance estimates from the ANOVA for the effects of cultivar and management on feed barley agronomic and quality variables collected at 14 Alberta environments. Environments (location and year), replicates within environments and their interactions with fixed effects were considered random effects. Significant effects (*P*>0.05) are in bold.

	Agronomic variables							Quality variables				
Effects	Plant height (cm)	Lodging[Z]	NDVI[Y]	Maturity (days)	Grain yield (MT ha^{-1})	N yield (kg N ha^{-1})	Kernel weight (g 1000^{-1})	Test weight (kg hl^{-1})	Grain protein	Grain starch	ADF[X]	NDF[W]
									----------(%)----------			
Cultivar (C)	**<0.001**	**0.002**	**<0.001**	**<0.001**	**<0.001**	**0.002**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Management (M)	0.443	0.803	**0.012**	**0.009**	**<0.001**	**<0.001**	**0.029**	0.101	0.054	0.207	0.159	**<0.001**
C x M	0.214	0.880	0.661	**<0.001**	0.276	0.255	0.540	**0.041**	0.125	0.056	0.264	**0.016**
Environment (E)[V]	158**	<1	<1	63	4**	1240**	10	5	2**	1**	<1**	1**
E x C (%)[U]	3**	<1	6**	6**	3**	2**	23**	39**	3**	5**	11**	8**
E x M (%)[T]	<1	7	6	<1	2**	2**	2	2	1	1	<1	1
E x C x M (%)[S]	<1	<1	1	<1	<1	<1	2	1	<1	<1	1	<1
Adjusted CV (%)	5	17	8	2	7	8	4	2	4	2	2	3

[Z]Lodging index (Berry et al., 2003). Lodging data was transformed with a log10 transformation to achieve normality and variance homogeneity.
[Y]Normalized difference vegetation index measured at BBCH 83-85.
[X]Acid detergent fiber
[W]Neutral detergent fiber
[V]Variance estimates for the environment random effect.
[U]Percentage of the variance associated with the environment × cultivar interaction; calculated as: [(variance estimate for environment x cultivar)/(sum of all variance estimates including environment)] × 100.
[T]Percentage of the variance associated with the environment × management interaction; calculated as: [(variance estimate for environment x management)/(sum of all variance estimates including environment)] × 100.
[S]Percentage of the variance associated with the environment × cultivar x management interaction; calculated as: [(variance estimate for environment x cultivar x management)/(sum of all variance estimates including environment)] × 100.
** *P* value < 0.01

Table 5-11. Least square means of feed barley agronomic responses to cultivar and management across 14 Alberta environments. Fisher's LSD mean separation was used to determine differences between cultivars. Treatments with different letters are significantly different (α =0.05).

Fixed effect	Plant height (cm)	Lodging[Z]	NDVI[Y]	Maturity (days)	Grain yield (MT ha^{-1})	N yield (kg N ha^{-1})	Kernel weight (g 1000^{-1})
Cultivar[X]							
CDC Austenson (2)	73c	15ab	0.40d	101b	7.03c	123.9d	47.1de
Xena (2)	73c	22c	0.36b	97a	6.83c	120.8cd	48.0e
CDC Coalition (2)	70b	10a	0.37bc	98a	6.81c	122.7d	45.9cd
Champion (2)	73c	20bc	0.38bcd	98a	6.79bc	120.1bcd	48.7e
Gadsby (2)	79d	23c	0.39cd	102b	6.48a	119.2abcd	51.2f
Busby (2)	79d	15ab	0.34a	97a	6.29a	116.6abc	48.7e
Vivar (6)	70b	16bc	0.38bc	98a	6.80bc	116.5abc	44.5bc
Amisk (6)	70b	13ab	0.38bcd	101b	6.64ab	120.2bcd	43.0ab
Breton (6)	80d	23c	0.37b	97a	6.56ab	114.5a	44.8bc
Muskwa (6)	66a	13ab	0.37b	96a	6.42a	115.4ab	41.6a
LSD 0.05	2.2	1.6	0.023	2.1	0.31	5.0	1.8
sed[W]	1.12	1.23	0.012	1.03	0.157	2.5	0.89
Management							
Standard	73	17	0.36a	98a	6.37a	113.5a	46.0a
Advanced	73	16	0.39b	99b	6.96b	124.5b	46.7b
LSD 0.05	0.7[ns]	1.5[ns]	0.02	0.8	0.26	4.6	0.62
sed	0.324	1.17	0.009	0.340	0.120	2.12	0.273

[Z]Lodging index of 0-100, where 0= upright and 100=completely lodged (Berry et al., 2003).

[Y]Normalized difference vegetation index measured at BBCH 83 to 85.

[X]Morphological spike type is indicated in parenthesis.

[W]Standard error of the difference between means.

Table 5-12. Least square means of feed barley quality responses to cultivar and management across 14 Alberta environments. Fisher's LSD mean separation was used to determine differences between cultivars. Treatments with different letters are significantly different (α =0.05).

Cultivar[Z]	Test weight (kg hl^{-1})	Grain protein	Grain starch	ADF[Y]	NDF[X]
		----------(%)----------			
CDC Austenson (2)	67.2c	10.4bc	60.8c	5.85d	16.1d
Xena (2)	66.5c	10.4bc	60.7c	5.87d	16.2d
CDC Coalition (2)	66.8c	10.7de	61.7e	5.64a	15.3ab
Champion (2)	67.1c	10.4bc	61.3d	5.64a	15.9c
Gadsby (2)	66.7c	10.8e	60.8c	5.72bc	15.5b
Busby (2)	67.2c	10.8e	61.2d	5.67ab	15.3a
Vivar (6)	61.7a	10.1a	59.7a	5.93d	17.1f
Amisk (6)	60.4a	10.7de	59.6a	5.92d	18.7g
Breton (6)	61.8a	10.2ab	60.0b	6.07e	17.0f
Muskwa (6)	64.8b	10.5cd	59.5a	5.76c	16.5e
LSD 0.05	1.7	0.23	0.25	0.07	0.21
sed[W]	0.86	0.12	0.125	0.036	0.105
Management					
Standard	64.8	10.4	60.5	5.80	16.5b
Advanced	65.2	10.5	60.6	5.81	16.3a
LSD 0.05	0.51[ns]	0.098[ns]	0.103[ns]	0.02[ns]	0.08
sed	0.230	0.045	0.0478	0.007	0.037

[Z] Morphological spike type is indicated in parenthesis.
[Y]Acid detergent fiber
[X]Neutral detergent fiber
[W]Standard error of the difference between means.

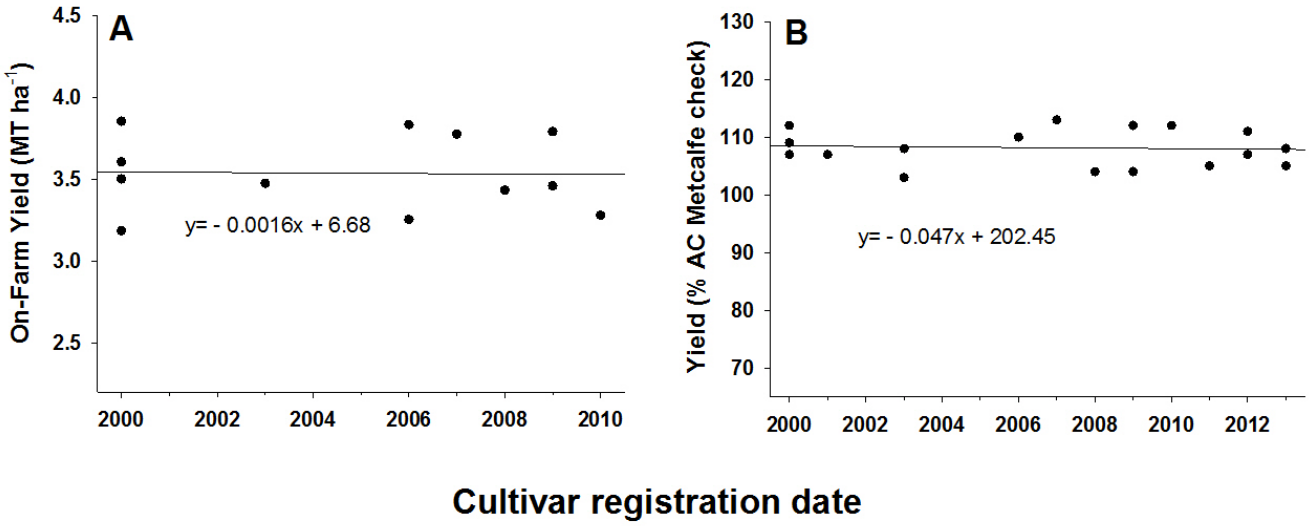

Figure 5-1. (A) Six-year average on-farm grain yield under Alberta rain-fed production for the 2010-2015 growing seasons of feed barley cultivars registered between 2000 and 2010. Adapted from Agriculture Financial Services Corporation (2016). (B) Performance of feed barley cultivars registered between 2000 and 2013 in the Alberta Regional Variety small-plot trials. Adapted from Alberta Agriculture and Forestry (2016a).

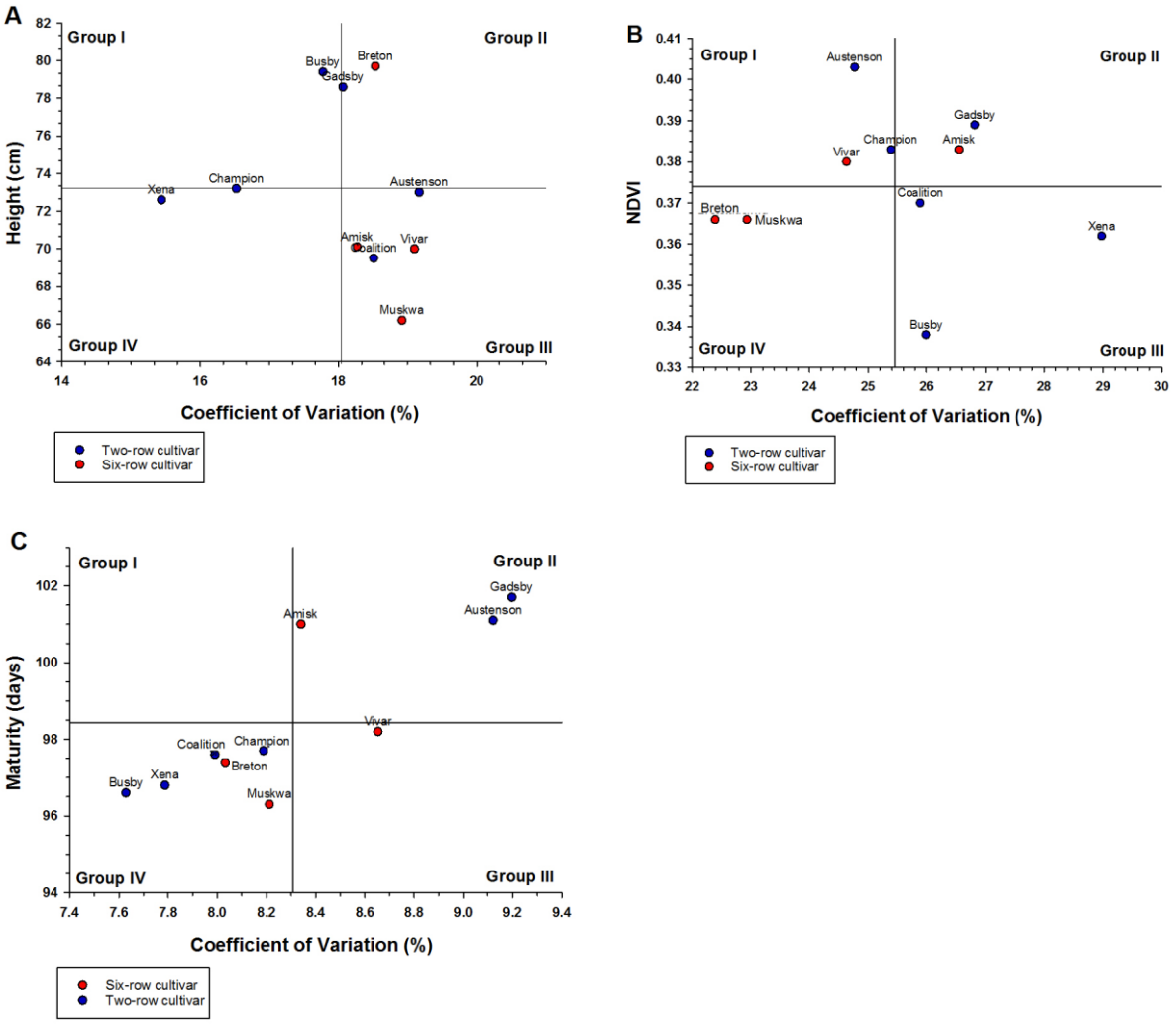

Figure 5-2. Biplots summarizing height (a), NDVI (b), and maturity (c) means vs. CV for cultivar data across 14 Alberta environments. Grouping categories: Group I: high mean, low variability; Group II: high mean, high variability; Group III: low mean, high variability; Group IV: low mean, low variability.

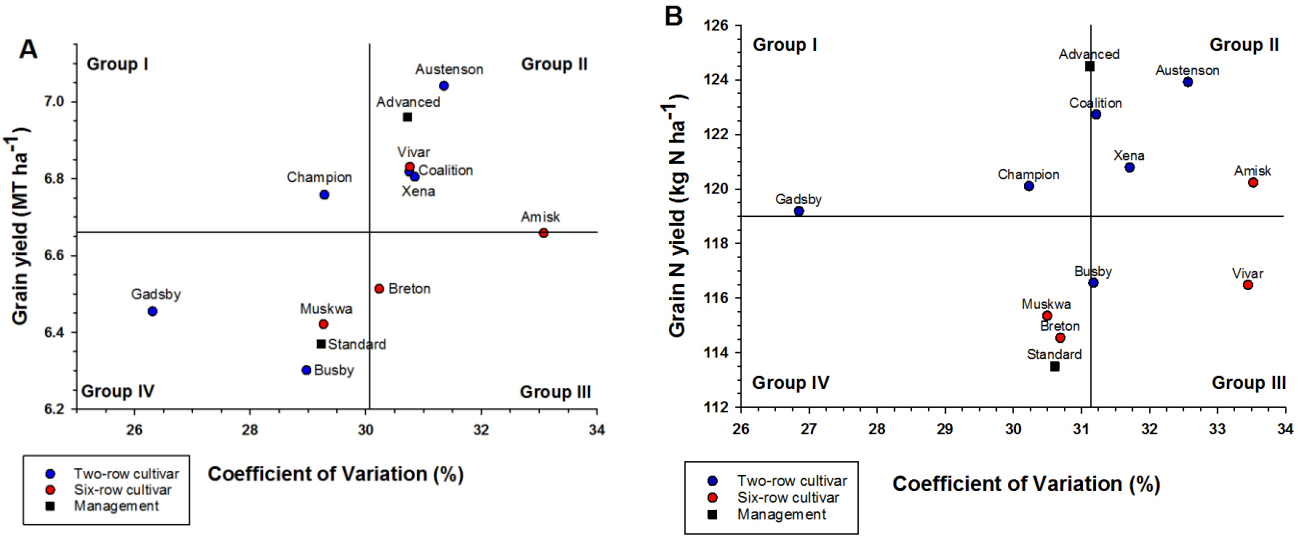

Figure 5-3. Biplot summarizing grain yield (a) and N yield (b) means vs. CV for cultivar and management data across 14 Alberta environments. Cultivar data was averaged across management levels and management data was averaged across cultivars. Grouping categories: Group I: high mean, low variability; Group II: high mean, high variability; Group III: low mean, high variability; Group IV: low mean, low variability.

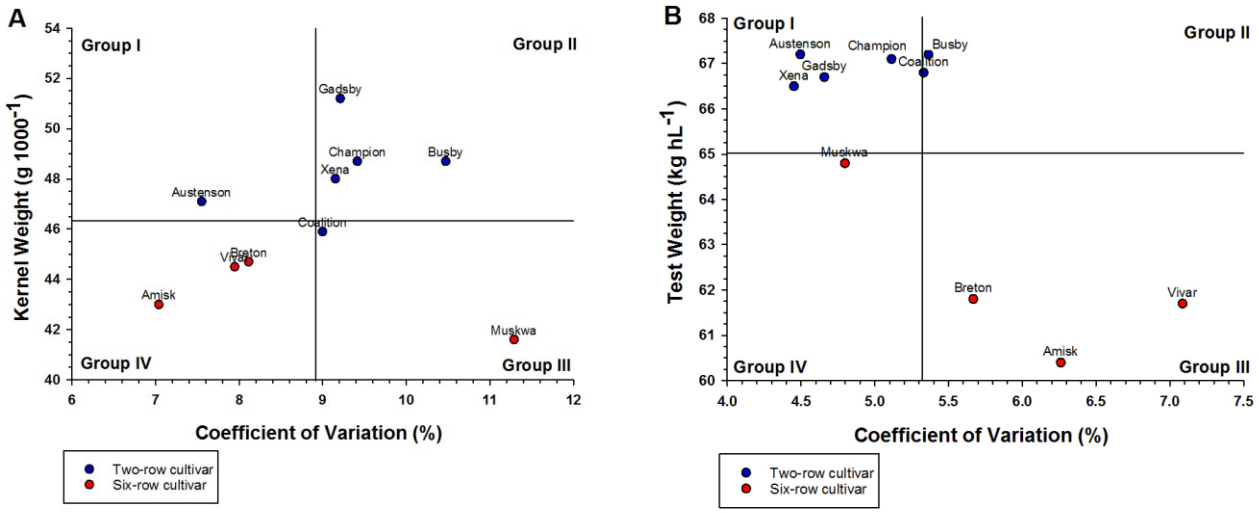

Figure 5-4. Biplots summarizing kernel weight (a) and test weight (b) means vs. CV for cultivar data across 14 Alberta environments. Grouping categories: Group I: high mean, low variability; Group II: high mean, high variability; Group III: low mean, high variability; Group IV: low mean, low variability.

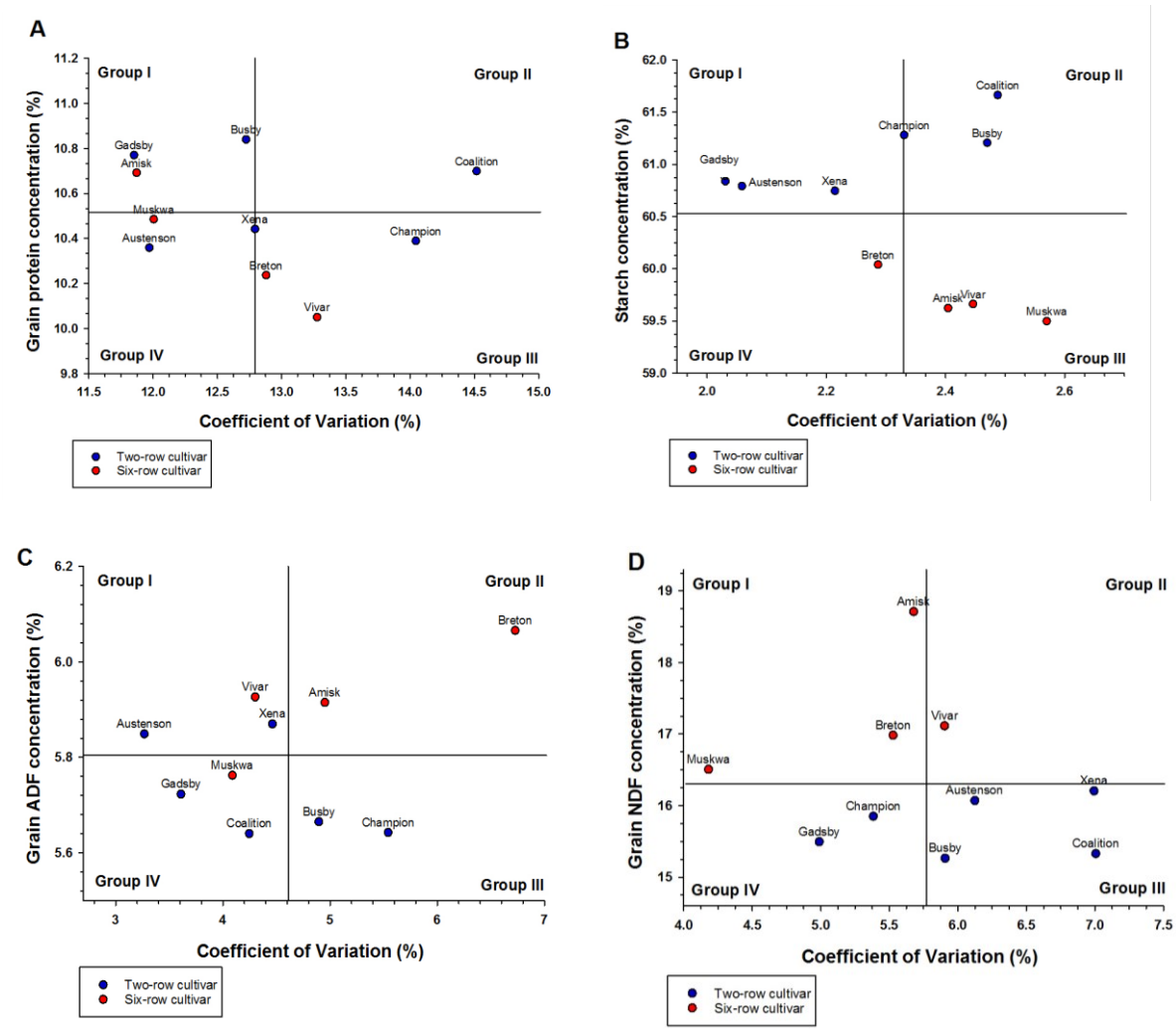

Figure 5-5. Biplots summarizing protein (a), starch (b), ADF (c), and NDF (d) means vs. CV for cultivar data across 14 Alberta environments. Grouping categories: Group I: high mean, low variability; Group II: high mean, high variability; Group III: low mean, high variability; Group IV: low mean, low variability.

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Chapter Six: Conclusion

6.1. Summary of Results

A small feed barley yield gains between 2 to 3% and negligible reductions in height and lodging were achieved using seeding rate, CCC, or foliar fungicides when baseline management included diverse crop rotation and a cultivar with genetic disease and lodging resistance. The previous crop rotation on trial sites in this study was reflective of the most common on-farm barley crop rotation in Alberta between 2007-2010. Of 223 surveyed fields between 2007 and 2010, 52% did not grow barley at all, and of the 48% of fields that did grow barley, 58% of these grew barley infrequently in the rotation; once every 4 years (personal communication, Julia Leeson, 2017). Interactions were minor or not present between post-emergence N and combinations of seeding rate, CCC, and foliar fungicide, however, seeding rate influenced yield component responses to CCC and yield response to dual fungicide application.

Post-emergence N was effective at increasing grain yield by up to 10% and 19% for the 34 and 68 kg N ha^{-1} post-emergence N treatments, respectively, and grain N yield by up to 14 and 22% for the 34 and 68 kg N ha^{-1} post-emergence N treatments, respectively, in the irrigated or high precipitation environments, or when the level of N applied at seeding was relatively low. Agronomic decisions surrounding post-emergence N application should be made in-season and need to consider the level of precipitation and other environmental conditions for maximum effectiveness. None of the agronomic management practices

examined markedly improved feed barley quality in terms of test weight, starch, ADF, and NDF concentration.

The negative or static genetic yield gains observed in recently registered cultivars (2008-2013) compared to the older cultivar Xena (2000) presents a major constraint for increasing feed barley yields and profitability in Alberta, especially for six-row cultivars. Cultivars responded similarly to advanced management under the low disease pressure conditions encountered in the study. Genetic lodging resistance remains a better tool than agronomic management to reduce lodging. The quality of two-row cultivars was superior to six-row cultivars, especially in rainfed environments with low growing season precipitation, where six-row cultivars were occasionally downgraded to Canada No. 2 Feed Grade because of low test weight. Feed barley producers should select high yielding two-row cultivars with genetic lodging resistance to maximize feed barley grain yield, standability, and grain quality.

6.2. Results Summarized by Research Objective

6.2.1. Determine the grain yield, agronomic, and quality responses of cv. Amisk feed barley to seeding rate, CCC, and foliar fungicide application combinations in Alberta production environments.

The quality factors starch, ADF, and NDF were not markedly improved with seeding rate, CCC, or foliar fungicide application. Increasing the target seeding rate from 240 to 355 plants m^{-2} had small effects on yield components that did not result in grain yield increases. This was in agreement with other western Canadian studies that reported negligible yield

gains above moderate (210 seeds m^{-2}) seeding rates. However, decisions surrounding seeding rate should be considered when applying CCC or dual fungicide, because the spike length and test weight responses to CCC, and the yield response to dual fungicide, depended on seeding rate. The higher seeding rate (355 plants m^{-2}) was required for dual fungicide applications to yield higher than a single application, and the moderate seeding rate (240 plants m^{-2}) was required for increased test weight when CCC was applied.

Foliar fungicides resulted in a small 3% average yield increase with no yield difference occurring between flag and late timings under the low disease pressure encountered across all environments in the study and when using a variety with genetic resistance to the major foliar diseases of barley in Alberta. Similar on-farm results may be expected when a cultivar with genetic foliar disease resistance is used because the preceding crop rotation in study environments was reflective of the average barley rotation, defined by barley every 0 or 1 in 4 years for 80% of the 223 surveyed fields in Alberta between 2007-2010 (Julia Leeson, personal communication, 2017). However, in-season agronomic decisions regarding foliar fungicide application would likely be required in environments with higher disease risk caused by barley grown more frequently in the rotation, and these conditions were not encountered in the current study. Late fungicide timing (after spike emergence) resulted in higher kernel weight compared to application to the flag leaf.

Application of CCC at BBCH 31 resulted in a small 2% yield increase, consistent across environments, that was unrelated to lodging. There was no marked impact of CCC on the height and lodging of Amisk barley, regardless of seeding rate. Making pre-plant decisions to select a cultivar with genetic lodging resistance remains the most effective tactic for lodging

reduction in barley. However, other GA inhibiting PGR active ingredients such as trinexepac-ethyl (TXP) are undergoing testing on barley in Alberta, and these may be introduced to Alberta for lodging control in barley to provide an additional solution to lodging.

When a genetically disease and lodging resistant cultivar such as Amisk, was grown under low disease pressure conditions, agronomic management including high seeding rate, chlormequat chloride, and foliar fungicide application, did not present a strong solution for markedly increasing feed barley grain yields in Alberta.

6.2.2. Determine the grain yield, agronomic, and grain quality responses of cv. Amisk feed barley to post-emergence N application in Alberta production environments.

Chapter four describes the effects of 0 to 68 kg ha^{-1} post emergence N applied as supplemental UAN and the urease inhibitor NBPT applied just prior to BBCH 30 on cv. Amisk feed barley production. The largest grain yield increases (between 4 to 10% and between 5 to 19% for the 34 and 68 kg ha^{-1} N treatments, respectively, compared to the control) and N yield increases from post-emergence N application usually occurred in environments with above-average growing season precipitation (usually near or above 300mm) or in environments where lower baseline rates of N were applied at seeding. Post-emergence N application in high temperatures and dry conditions decreased grain yield by up to 19% and should be avoided. In-season agronomic decisions for post-emergence N application based on observed precipitation and the amount of N applied at seeding are required for maximum effectiveness.

Not all post-emergence N applied was recovered in the grain because the N applied post-emergence was always greater than the grain N yield. The grain protein increase

observed with increasing rate of post-emergence N was greater in environments with lower rates of N applied at seeding. Post emergence N had small or no effect on maturity and lodging, respectively, in the genetically lodging resistant cv. Amisk barley. Therefore, the practice did not result in any negative agronomic consequences in this cultivar. The feed barley grain quality parameters test weight, starch, ADF, and NDF concentration also had neutral or small responses to post-emergence N application. Therefore, post-emergence N provided an avenue to increase grain yield in irrigated environments or those with high growing season precipitation without any agronomically significant negative lodging, maturity, or quality responses in cv. Amisk barley. Small grain yield increases, or grain yield decreases, may result if post-emergence N applications are not based on in-season precipitation and temperature information and the level of N applied at seeding. The addition of the urease inhibitor NBPT increased grain yield and N yield in 1 of 14 environments and had no effect on other variables.

6.2.3. Quantify interactions between post-emergence N and combinations of seeding rate, CCC, and foliar fungicide for cv. Amisk feed barley in Alberta environments.

Interactions were absent between post-emergence N application and seeding rate, CCC, and foliar fungicide application for all response variables except NDF. The 0.1% decrease in NDF for late and dual fungicide with post-emergence N application was too small to be of biological or agronomic significance. The absence of meaningful interactions in the study may be attributed to environmental conditions with low disease pressure, the absence of

biotrophic pathogens and the predominance of necrotrophic pathogens at relatively low levels, and the use of a cultivar with genetic resistance to foliar disease and lodging.

6.2.4. Determine the performance and response of 10 feed barley cultivars to advanced agronomic management and determine if responses are cultivar-specific.

Cultivar performance and the response of 10 feed barley cultivars to advanced management were investigated and described in Chapter Five. The highest yielding cultivars in average to above average precipitation or irrigated environments were the two-row cultivars CDC Austenson, Xena, and CDC Coalition. With the exception of the older six-row cultivar, Vivar, the newer six-row cultivars Amisk, Muskwa, and Breton were significantly lower yielding than the highest yielding two-row cultivars and six-row cultivars are therefore not recommended for high yielding feed barley production. Xena had among the highest lodging severity in the study, whereas CDC Austenson and CDC Coalition had intermediate and low lodging, respectively. CDC Coalition should be grown to simultaneously achieve high grain yield, high grain quality, and excellent standability in environments with average or above average precipitation or irrigation. The two-row cultivar, Champion, yielded 7% higher than then next highest yielding cultivar in low precipitation environments, and this cultivar should be grown in environments with historically low rainfall to help mitigate drought-related risk.

Importantly, the low yields of recently registered cultivars (2008-2013 registrations) compared to older cultivars such as Xena and Vivar, registered 8-13 years prior (2000), are a major impediment for barley yield increase and for the retention of barley in the Alberta crop rotation.

The quality of two-row cultivars was superior to six-rows because of higher test weights, higher starch, lower NDF, and low to intermediate ADF concentrations. Six-row cultivars presented a marked quality risk because of low test weight that often resulted in downgrading, especially in environments with low growing season precipitation, and therefore should not be grown in Alberta for feed barley production.

The 9.3% average grain yield gain observed across cultivars and environments for advanced compared to standard management was close to three times greater than the largest genetic yield gain observed for recently registered cultivars (2008-2013) compared to older cultivars such as Xena (2000). Irrigated environments or those with high precipitation (between 251 and 502mm) resulted in large advanced management yield gains (between 8-18%) compared to drier rainfed environments where yield gains were small, between 1-3%. The decision to implement advanced management practices should occur when precipitation or expected precipitation is high. Small or infrequent quality increases resulted from advanced management. Lodging was also not improved with advanced management and cultivar selection remains the best tool to attain high quality and standability in feed barley cultivars.

Interactions between cultivar and management were infrequent and small in magnitude when they occurred, which was for maturity, test weight, and ADF concentration. The low disease pressure in study environments may have contributed to the lack of interactions between cultivar and management. The small differences in magnitude of cultivar response to management were statistically interesting but they were not of biological or agronomic significance. Therefore, under the low disease pressures observed in the study, cultivars did not require differential agronomic management. The preceding crop rotation and

the low disease conditions encountered in the study were reflective of the average on-farm barley rotation in Alberta. This rotation consisted of the majority of 223 surveyed fields having 0 or 1 year of barley every 4 years, between 2007-2010 (Julia Leeson, personal communication, 2017). Under these conditions, differential management of feed barley cultivars may not be required to maximize on-farm yields. However, higher disease pressures, which were not encountered in the present study, may demand differential management of cultivars ranging in genetic disease resistance.

To achieve maximum grain yield, grain quality, and excellent standability in environments with average or above average precipitation or in irrigated environments, CDC Coalition is recommended. CDC Austenson may be grown for slightly higher grain yields, and intermediate standability in the same environments. Advanced management is also recommended in these environments to achieve grain yield increases between 8 and 18%. Champion should be grown in areas with historically low precipitation to help mitigate the risk of yield loss caused by dry environmental conditions, and advanced management should also not occur here. The six-row cultivars tested should not be grown in Alberta, regardless of precipitation level, because of their lower test weight quality and, for the newest six-row cultivars, lower grain yields.

6.3. Future Research

- Additional N, applied post-emergence, resulted in small to modest yield increases when N fertilization at seeding targeted area average yield goals. However, in environments where lower amounts of N were applied at seeding, post-emergence N

resulted in larger yield increases, suggesting that split applications of the same total amount of N at seeding and post-emergence may provide a more economic method for yield increase and risk mitigation. Therefore, split N applications (same total N split between seeding and just prior to BBCH 30) should be investigated in western Canadian growing conditions to assess the yield, risk, and economic responses.

- Chlormequat chloride showed limited efficacy on lodging improvement in feed barley. However, other GA inhibiting PGRs such as trinexepac-ethyl (TXP) are registered for use on feed barley alone or in combination with CCC elsewhere globally, and determining the effect of CCC and TXP in combination on feed barley cultivars may assist in reducing lodging.
- The low disease pressure present in the study likely reduced the magnitude fungicide response and may have contributed to a lack of differential responses to fungicide application timing. As such, survey work to assess the occurrence of low diversity barley rotations and high disease pressure in current Alberta barley fields may be conducted. If survey work confirms disease pressure is low, extension messaging could be extended to producers to reduce barley foliar fungicide use in low disease environments with genetically resistant varieties. Alternatively, foliar fungicide application timing and cultivar response to advanced management should be tested under higher disease pressure conditions reflective of a less diverse crop rotation to determine the yield benefits, grain quality (test weight) benefits, and the presence of differential cultivar response under high disease pressure conditions.

- The lack of genetic yield gains in recently registered cultivars demands alternatives for feed barley production profitability. Investigation into the potential of high yielding malt barley varieties to be managed for feed end-use using higher rates of N fertility than would traditionally be used for malt barley production may provide a solution.

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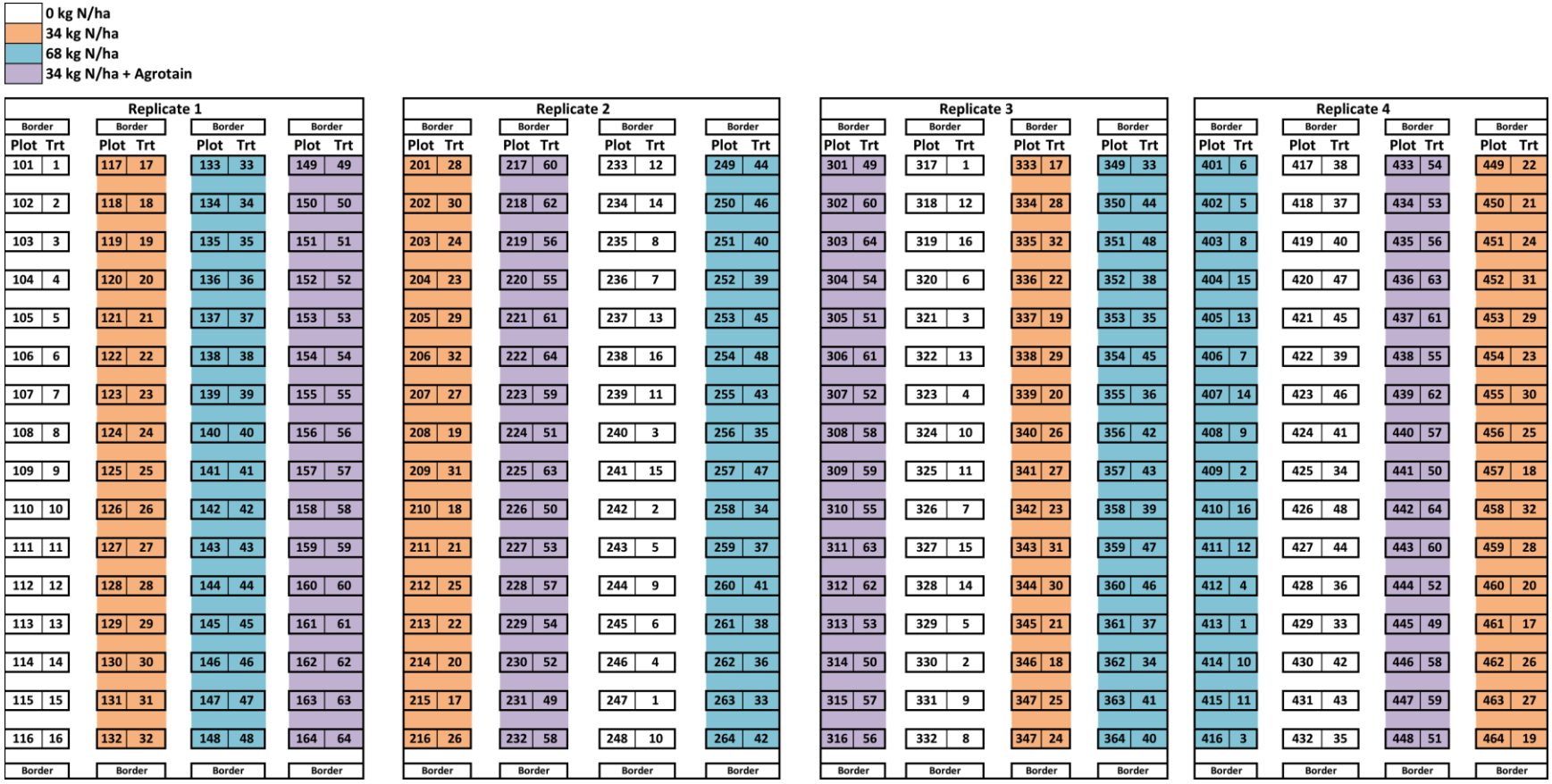
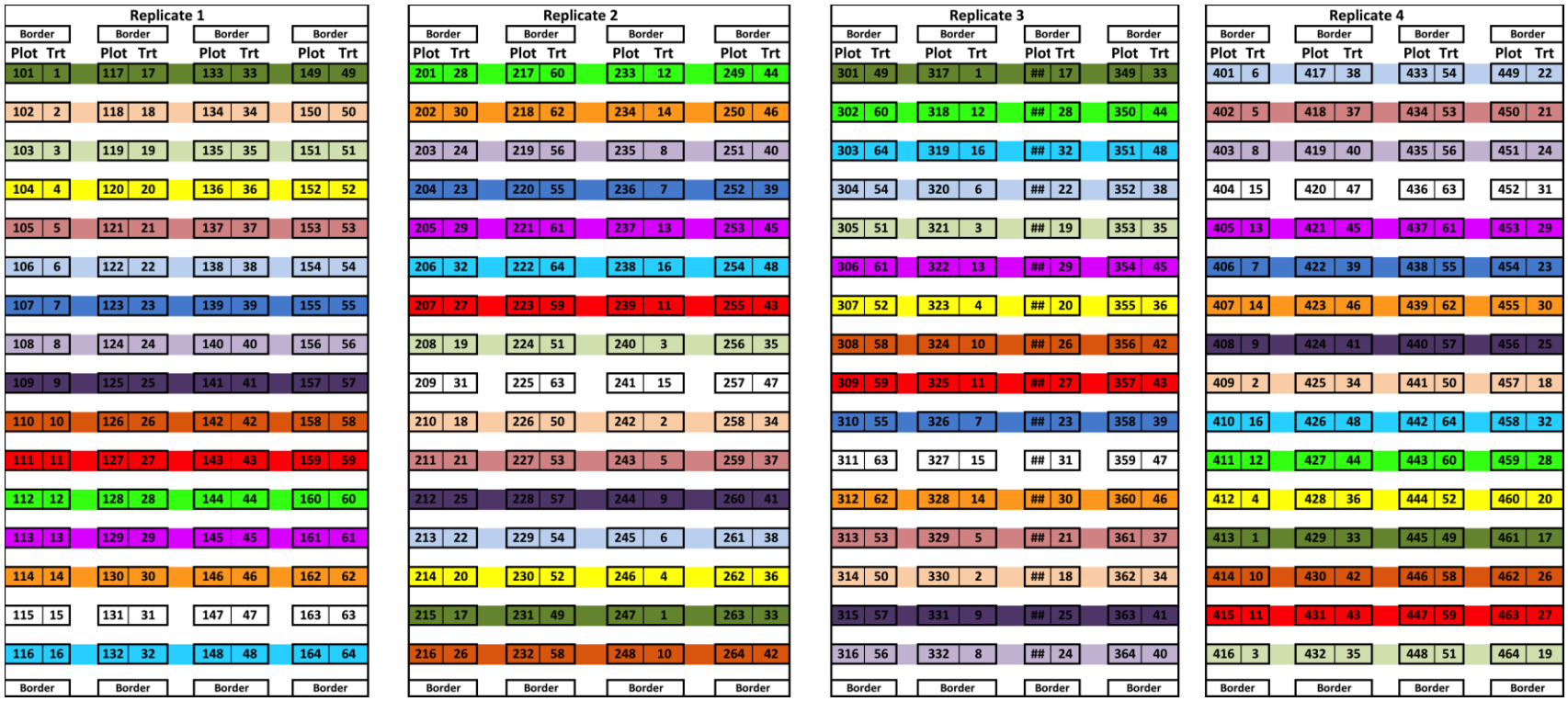
Appendix



Appendix Figure 1. Horizontal strip (post-emergence N level) orientation within the trial, indicating replicate, plot number, and treatment number (64 experimental treatments). Horizontal strips were randomized within each replicate.



Appendix Figure 2. Vertical strip (SRxPGRxFung combination with 16 levels) orientation within the trial, indicating replicate, plot number, and treatment number (64 experimental treatments). Treatments comprising each vertical strip were randomized within each replicate. Different colours indicate a different vertical strip.