Evaluation of New Herbicide Options for the Control of Foxtail Barley (*Hordeum jubatum*) in Spring Wheat

by

Mathew Vercaigne

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

Master of Science

in

Plant Science

Agricultural, Food and Nutritional Science

University of Alberta

Abstract

Foxtail barley (*Hordeum jubatum* L.) is a perennial grass increasing in prevalence in western Canadian cereal fields. Seedling, over-wintering-juvenile and mature stages makes herbicide timing and selection challenging for producers. Field experiments were conducted at six sites over two years to characterize the response of established seedling and mature foxtail barley populations to combinations of short residual herbicides applied PRE and POST seeding with glyphosate. Experiment one evaluated PRE short residual herbicides: propoxycarbazone (at 7.5 and 10 g ai ha^{-1}), flucarbazone/tribenuron and pyroxasulfone at 21.79 and 150 g ai ha^{-1}, respectively, tank-mixed with glyphosate at 450 and 900 g ae ha^{-1}. Experiment two evaluated combinations of propoxycarbazone, flucarbazone/tribenuron and pyroxasulfone with the high rate of glyphosate followed by a POST application of thiencarbazone-methyl at 4.94 g ai ha^{-1}. Foxtail barley seedling and mature populations varied among sites, Scott having the highest mature population at 76 mature plants m^{-2}, while St. Albert had the highest seedling population at 81 seedlings m^{-2}. Visual estimation of herbicide control, seedling emergence density, foxtail barley biomass, wheat biomass and wheat seed yield were quantified. Herbicides applied pre-seeding in the absence of glyphosate failed to control mature foxtail barley. However, ALS1 at 10 g ai ha^{-1}, flucarbazone/tribenuron and pyroxasulfone applied in combination with the high rate of glyphosate increased control to 73.9%, 72.1% and 74.4% at Lethbridge 2016, Olds and Scott, respectively. Moreover, at Lethbridge 2015, Vermilion and St. Albert, control increased to 90.4%, 90.8% and 89.3%, respectively.
Pyroxasulfone tank-mixed with the high and low rate of glyphosate reduced foxtail barley

seedling emergence compared to rates of glyphosate applied alone (29 to 4 seedlings m^{-2}). Glyphosate at both rates applied with and without residual herbicides reduced foxtail barley biomass compared to the non-treated check. However, glyphosate at the high rate did not reduce foxtail barley biomass more than the low rate (49.91 to 27.45 g m^{-2}). The addition of residual herbicides to the high rate of glyphosate did not increase wheat biomass or seed yield. Tank-mixing ALS1 at 10 g ai ha^{-1} with the high rate of glyphosate followed by ALS 2 reduced foxtail barley biomass compared to the high rate of glyphosate applied alone (28.67 to 4.53 g m^{-2}). Seedling recruitment varied among sites and was observed over an extended period in spring and post-harvest, suggesting that both pre-seeding and post-emergent control timings along with a multi-year strategy may be required to reduce future foxtail barley populations. This research indicates that by adding a short-residual soil applied herbicide to glyphosate at a pre-seeding timing, followed by a post-emergent application of a herbicide that can suppress foxtail barley, producers can achieve control of foxtail barley over the growing season in spring wheat. Having multiple herbicide control options for foxtail barley will aid producers in successfully controlling this problematic weed, in-turn, increased grain yield and profitability.

“The science of today is the technology of tomorrow”

Edward Teller

Acknowledgements

I would like to thank my supervisor Dr. Linda Hall for her mentorship and support throughout my project. Furthermore, I would like to thank Dr. Hall for giving me the opportunity to present my data at multiple academic conferences, which has served me as very important networking and skill development events.

I would also like to express my sincerest appreciation to Eric Johnson; Your thoughts, expertise, support and willingness to be my mentor throughout the past 3.5 years has excelled my education and career beyond a level ever thought possible. Thank you for all that you have done for me.

I would also like to thank my advisory committee for their comments and aid in the statistical analysis of my project: Dr. Cam Carlyle and Dr. Hugh Beckie. As well, I would like to thank Kelly Patzer for his critical input in this project, as well as taking the time to discuss concerns and findings throughout the growing seasons for this project.

To my fellow grad students, without your guidance and expertise throughout my program, this program definitely would have taken me much longer to complete, thank you for all of your help: Breanne Tidemann, Joseph Aidoo, Laurel Perrott, Amy Mangin and Brendan Alexander.

In addition, I would like to thank our Weed Science lab group for all of their help with field work and processing over the past 2 years: Elise Martin, Bryanna Jeske and Keith Topinka. Seeding and biomassing would not have happened without your help. I would also like to acknowledge my site collaborators: Ryan Low, Bill Hamman, Jessica Weber and Gazali Issah.

Finally I would like to deeply thank Nikki Burton for all of her help and support throughout my project. Not only did your guidance greatly help me complete this project in a timely manner, but whenever I had an issue with school or life, you were always the first phone call I made to help me sort it out. Thank you for all that you do for me.

This thesis was made possible by funds provided from Bayer CropScience and Alberta Crop Industry Development Fund Ltd.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

ACCase	Acetyl-CoA Carboxylase
ac	Acre
ae	Acid equivalent
ai	Active ingredient
ALS	Acetolactate synthase
APPR	Rainfall at time of product application (1 week prior-2 weeks following) (mm)
ANOVA	Analysis of variance
BBCH	Bayer, BASF, Ciba-Geigy and Hoechst (Growth scale stage)
C	Celsius
cm	Centimeter
DAT	Days after treatment
EC	Emergence (cumulative)
g	Gram
GDD	Growing Degree-day, base 5^{o}C
GSR	Growing season rainfall (mm)
ha	hectare
IMI	Imidazolinone herbicide
IWM	Integrated Weed Management
kg	Kilogram
kPa	Kilopascal

L	Litre
LTA	Long-term average
m	Meter
mL	Millilitre
N	Nitrogen
OM	Organic matter
POST	Post-emergent
PRE	Pre-seeding
SU	Sulfonylurea herbicide
VLCFA	Very Long Chain Fatty Acid
WDG	Water dispersible granule
WSSA	Weed Science Society of America

Contributions of Authors

The contributions made by the candidate and the co-authors to the completion of this of this thesis are described below. Chapter three of this thesis is written by the candidate. The candidate was responsible for conduction of the trials at all sites, compilation of data, statistical analysis and writing of the manuscript. Dr. Cam Carlyle assisted with the statistical analysis. Chapter four of this thesis was written by the candidate. The candidate was responsible for conduction of the trials at all sites, compilation of data, statistical analysis and writing of the manuscript. Dr. Tozzi assisted with the statistical analysis of this chapter. Technical and field support in both Chapters three and four was provided by Elise Martin, Bryanna Jeske and Keith Topinka as well as other graduate students in the Weed Science program. Dr. Linda Hall was the graduate student supervisor for the candidate and worked with the candidate on the writing of all manuscripts, experimental designs and advised the candidate throughout his program. Field trials were placed at Hamman Ag Research (Dr. Bill Hamman) in Lethbridge, Alberta and Western Applied Research Corporation (Jessica Weber) at Scott, Saskatchewan. Site collaborators were responsible for monitoring seedling recruitment for periods throughout the study, as well as site maintenance.

Chapter One: Introduction
1.1. Background

Spring wheat (*Triticum aestivum* L.) is widely grown across the western Canadian prairie provinces and is one of the country's largest exported grain commodities (DePauw et al. 2011; StatsCan 2015). Canadian spring wheat is of high export value due to its high quality and protein content (Curtis 2002). Producers include spring wheat in their crop rotation as it is capable of withstanding adverse environmental conditions while maintaining desirable yields (Iqbal et al. 2016). Likewise, spring wheat is a strong competitor against detrimental weed species (Beres et al. 2010).

Spring wheat agronomic and cultural practices have shifted over time in western Canada. Prior to the 1980's, spring wheat was typically managed in a wheat-fallow rotation in many parts of the Canadian prairies (Johnson and Ali 1982; Lindwall and Anderson 1981). However, due to concerns of soil erosion and maintaining adequate soil moisture to produce crops, conservation tillage practices have become widely adopted by many producers in western Canada (Zentner et al. 2002). Although conservation tillage systems have addressed and resolved concerns with soil erosion, new challenges have arisen for producers that have adopted these systems. Tillage operations were utilized as a primary weed management strategy for controlling simple perennials because they can uproot and control established plants (Mohler 2001). Consequently, a reduction of fall and spring tillage operations of grain producing fields has led to the increase of abundance and density of perennial weeds in western Canadian cropland (Blackshaw et al. 1994, 2008; Derksen et al. 2002; Moyer et al. 1994; Wruke and Arnold 1985).

The increase in perennial weeds has been offset in part by the widespread use of glyphosate. Producers currently rely on herbicides and competitive crops as their primary control options for managing weed populations. Glyphosate is commonly applied as a pre-seeding (PRE) or pre-emergent burndown to control emerged weeds prior to crop emergence (Blackshaw et al. 2008). Moreover, producers commonly use glyphosate as PRE because it is both effective and economical (Blackshaw et al. 2008). However, glyphosate does not have residual weed control, rendering it ineffective on weed seedlings that emerge following application.

Foxtail barley (*Hordeum jubatum* L.) is a native perennial bunch grass species that has increased in abundance and density in western Canada as a result of the adoption of conservation tillage systems (Best et al. 1978; Leeson et al. 2005). Foxtail barley establishes in rangeland, ruderal areas and cropland (Best et al. 1978). Foxtail barley tolerance of high soil salinity and high soil moisture allow it to colonize newly disturbed areas (Wilson 1967). Foxtail barley is a simple perennial that does not reproduce by rhizomes or root stocks like creeping perennial grass species such as quackgrass (*Elytrigia repens*) (Donald 1990). This weed species uses seed production as its primary reproductive strategy and the seed is easily distributed by wind and livestock (Best et al. 1978). Foxtail barley has two seed germination cohorts; seeds that are dispersed from the mature plants in the fall readily germinate if environmental conditions are favorable; and seed that does not germinate in the fall and overwinters on the soil surface can potentially germinate in the spring when conditions are adequate (Badger and Ungar 1989; Chepil 1946).

Tillage adequately controls foxtail barley as it has a shallow fibrous root system that is easily disrupted by tillage operations (Donald 1990). Likewise, foxtail barley seeds will not germinate when buried in the soil profile at depths greater than 7.5 cm (Banting 1979). Timings and rates of glyphosate application to control foxtail barley have been evaluated in various studies. Glyphosate applied at 800 g ha^{-1} provided 70% control when applied post-harvest (Blackshaw et al. 2000). Glyphosate applied at 800 g ha^{-1} in a spring application provided 100% control of emerged foxtail barley seedlings, however in-crop (POST) herbicides are required to control late emerging spring seedling and seedlings that emerge throughout the growing season (Blackshaw et al. 1998, 2000). There are limited PRE and POST herbicide options to control foxtail barley in spring wheat (Blackshaw et al. 1998; Saskatchewan Ministry of Agriculture 2016). A formulated herbicide combination of flucarbazone-sodium and tribenuron-methyl is marketed as a PRE herbicide in western Canada for foxtail barley control in spring wheat (Saskatchewan Ministry of Agriculture 2016). ACCase-inhibitor herbicides such as quizalofop and sethoxydim are also registered for suppression of foxtail barley in oilseed and pulse crops.

Several new short residual herbicides have been developed for wheat crops. Research is required to test new short residual herbicides for activity on mature and seedling foxtail barley in both PRE and POST applications. An optimum herbicide regime is also required to enhance producers' control of this weed in short spring wheat rotations.

1.2. Research Objectives

1.2.1. Determine effective rate of glyphosate required to control foxtail barley in a pre-seeding application.

Weed densities and environmental conditions can alter glyphosate's effectiveness on foxtail barley control and glyphosate recommended rates vary widely. To establish a baseline for control of foxtail by glyphosate, we compared two rates in experiments detailed in Chapter 3. The following hypothesis was made:

- A rate of 900 g ae ha^{-1} of glyphosate will provide greater control of mature foxtail barley compared to 450 g ae ha^{-1}.

1.2.2. Determine if tank-mixing a short residual product pre-seeding with glyphosate increases mature and seedling foxtail barley control.

PRE applied short residual herbicide efficacy on mature and seedling foxtail barley has not been reported in western Canada. New herbicides products with different modes of action: Inferno® Duo (flucarbazone-sodium, tribenuron-methyl) and Focus® (Pyroxasulfone, carfentrazone) have been introduced into the western Canadian marketplace in recent years. As well, propoxycarbazone-sodium is currently under development for potential use in western Canada. There are no reports of foxtail barley control by these herbicide formations applied in combination with glyphosate. This objective was investigated in Chapter 3 and the following hypothesis was established:

- The short residual herbicides used in this experiment will increase foxtail barley control when tank-mixed with glyphosate.

1.2.3. Determine if efficacy of short residual herbicides varies on foxtail barley.

Control of foxtail barley with short residual herbicides under development in western Canada have not been reported. Their efficacy on foxtail barley was evaluated in Chapter three and the following hypothesis was made:

- Control of foxtail barley will be similar with the short residual herbicides used in this experiment.

1.2.4. Determine if tank-mixing two residual products with glyphosate provides greater control of foxtail barley compared to one residual product.

The interactions of short residual herbicides in combination with glyphosate have not been studied in western Canada. Potential interactions between the herbicides such as antagonism and synergism are unknown. This objective was investigated in Chapter three and the following hypothesis was made:

- Two short residual herbicides tank-mixed with glyphosate will provide significantly greater control of foxtail barley than a single residual herbicide alone.

1.2.5. Determine if incorporating a PRE application of glyphosate and short residual herbicides followed by a POST application of short residual herbicide improves foxtail barley control.

Previous literature has suggested that a combination of PRE and POST herbicide application are required to achieve full control of foxtail barley during the growing season. At the time of this study there were no PRE or POST herbicide options other than glyphosate to control foxtail barley in spring wheat. With new herbicide products becoming available in western Canada, their efficacy on foxtail barley when applied in conjunction are unknown. Finding an effective herbicide regime is essential to obtaining complete control of foxtail barley in spring wheat. This objective was investigated in Chapter three and the following hypothesis was made:

- Applying short residual herbicide(s) in combination with glyphosate at a pre-seeding timing followed by a POST application of thiencarbazone-methyl will provide significantly greater control than using one herbicide timing alone.

1.2.6. Determine cumulative seedling recruitment of foxtail barley for the growing year.

Understanding the time of foxtail barley seedling recruitment is crucial for developing an effective herbicide regime system. Foxtail barley seedling recruitment occurs both in the fall and spring of the growing season. The percentage of seedling recruitment in both spring and fall varies depending on environmental factors such as soil moisture, accumulated growing degree days and intraspecific competition. A more robust understanding of the factors and pattern of seedling recruitment will aid in determining the effectiveness of selective herbicide application timings. This objective was investigated in Chapter four and the following hypothesis was made:

- Foxtail barley seedling recruitment will vary among sites. Factors such as soil moisture, accumulated growing degree days and intraspecific competition will cause shifts in cumulative seedling recruitment throughout the growing season.

Chapter Two: Literature Review

2.1. Spring wheat production in western Canada

Spring wheat (*Triticum aestivum* L.) is a major crop in Canada, produced primarily in the prairie provinces (DePauw et al. 2011). In 2016, there were 6.25 million hectares of spring wheat grown on arable land in Canada, of that, 6.08 million hectares were grown in the prairie provinces (StatsCan 2016a). In Alberta, 5.86 million acres were sown to spring wheat in 2015, accounting for 24.2% of arable land used for annual crop production (Government of Alberta, 2016). Spring wheat is the second largest crop seeded in the prairie provinces, following canola (StatsCan 2016b). Canadian wheat is in high export demand because of its high quality and protein content (Curtis 2002). In 2015, Canada exported 17.9 million tonnes of spring wheat, making the crop the highest exported grain commodity in the country (StatsCan 2015).

Spring wheat's adaptability in adverse environmental conditions, along with its ability to compete with weeds makes it a desirable crop for western Canadian producers (Iqbal et al. 2016; Beres et al. 2010). Over the past 100 years, plant breeding programs have focused on improving important agronomic traits of spring wheat such as grain yield, lodging resistance, disease resistance, early plant maturity, and end use quality (Iqbal et al. 2016). Wheat producers in western Canada face a number of production and marketing challenges including economic returns due to over-supply in the market place, challenging end-use quality standards in conditions that may include lodging, frost damage weeds, and insect pests (Beres et al. 2010; McCaig and DePauw 1995; McCallum and DePauw 2008). Although pesticides are used to aid producers in suppressing or preventing economical pest damage, plant breeders are continuously developing new cultivars with stronger agronomic traits and disease packages using new technologies such as doubled haploid technology and marker assisted breeding to develop cultivars with strong desirable traits for Canadian producers (DePauw et al. 2011; Thomas and Graf 2014).

Prior to the 1980's, wheat-fallow rotations were a common practice among western Canadian grain producers. Conventional tillage practices in fallow years were thought to conserve soil water, allow for a release of soil nitrogen, increase the success of seedling establishment, and enhance weed control (Johnson and Ali 1982; Lindwall and Anderson 1981). However, soil erosion concerns between 1970 and 1980 and the availability of alternative herbicides for control of weeds prompted growers to adopt no-till or conservation tillage (Zentner et al. 2002).

In 1992, western Canadian spring wheat acres peaked at 12.4 million hectares (StatsCan 2016a). Oilseed and pulse cultivar improvements, along with favorable economic return-on-investment has caused an increase in production of oilseed and pulse crops within the prairie provinces (McCallum and DePauw 2008; Beckie et al. 2006). In 2015, 8.0 and 3.7 million hectares were seeded to canola and pulse crops in the prairie provinces, respectively (StatsCan 2016b). The combination of reduced summer fallow acres and increased acres used for oilseed and pulse production has caused a reduction in acres sown to wheat (Campbell et al. 2002; Derpsch et al. 2010). Although spring wheat acreage has been declining in recent years, the crop still makes up a large proportion of crop rotations in western Canada. In Saskatchewan, 46% of producers grow spring wheat

1 in 2 years, and 23% 1 in 3 years (H. Beckie unpubl data). Short rotations of wheat-canola are also somewhat common in the prairies, as producers perceive this to be the strongest rotation for economic return (Beckie et al. 2011). In western Canada, spring wheat is primarily grown under conservation tillage systems. The combination of this system along with short crop rotations has led to new challenges for producers when managing perennial weed populations.

2.2. Direct seeding and influence on perennial weeds

There are two primary classifications of reduced tillage systems used in western Canada. Derpsch (2003) defines zero-tillage (no-till) as the practice of planting into an unprepared seedbed while not disturbing more than 1/3 of the soil surface. Conservation tillage is defined as any tillage operation that leaves more than 30% of plant residue at the soil surface after seeding (Derpsch 2003). Conservation tillage systems were introduced to western Canada after severe soil erosion problems occurred throughout the 1930's (Awada et al. 2014). Adoption of conservation tillage systems began to increase in the 1970's, however, because of economic, technical, political, and social reasons, mass adoption of the system did not occur until the 1990's (Awada et al. 2014). No-till production systems are now widely used in the black and dark brown soil zones of western Canada, while some producers in the light brown soil zone continue to use conventional tillage. As of 2011, 61.6% of arable land in the Canadian prairies is managed using no-till production. Moreover, 23.5% of arable land in the prairies uses a conservation-tillage management regime (StatsCan 2014). Along with the benefit of preventing soil erosion, direct seeding management also retains more soil moisture and prevents the loss of gaseous nitrogen to the environment, whereas conventional tillage does not (Lafond and Derksen 1996; Tiessen et al. 2010). Additionally there are time management benefits, resulting in earlier seeding and associated yield benefits.

Technological advancements have allowed for the successful adoption of no-till practices in western Canada. Machinery such as no-till air seeders and openers, along with reduced input costs for herbicides, such as glyphosate, are among the reasons why no-till production systems have been successfully implemented in western Canada (Collins and Fowler 1996; Gray et al. 1996; Zentner et al. 2002). An advantage of no-till systems is the practice of direct seeding into an undisturbed seedbed, which allows producers to make fewer or no passes in the field prior to seeding to prepare the seedbed for planting (Zentner et al. 2002). Furthermore, a pre-seeding (PRE) or post-emergent (POST) application of glyphosate or a mixture of glyphosate with products designed to control glyphosate-resistant canola or improve efficacy is a common practice among producers that utilize no-till systems as it is both economical and highly efficacious on emerged weed species that cause economic yield losses if left uncontrolled (Blackshaw et al. 2008). The practice of direct seeding combined with a PRE application of glyphosate reduces producers' labour and fuel costs. A 4-year study conducted by Lafond et al. (1993) at Indian Head, Saskatchewan showed that spring wheat planted on stubble using conservation tillage resulted in \$57.94 ha^{-1} greater net return than compared to using a conventional tillage system.

Although no-till production systems have been successful at reducing soil erosion and improving soil moisture, other concerns around this production practice have become apparent in the last decades. In particular, a consequence of no-till systems is the shift in weed species caused by removing primary tillage as a main weed control option (Blackshaw et al. 1994, 2008; Derksen et al. 2002; Moyer et al. 1994; Wruke and Arnold 1985). Tillage can affect weed growth and reproduction in multiple ways such as uprooting mature plants, dismembering and burying growing weeds and dormant perennial organs, which can cause plant death, or inducing dormancy in some cases (Mohler 2001). For example, infrequent tillage operations of quackgrass (*Elytrigia repens*) populations can fragment the weeds rhizomes, which disperses the rhizome buds along the trajectory of the tillage operation, leading to an increase in weed dispersal and germination (Chandler et al. 1994). Tillage operations can also influence seed germination within the seedbed by moving seeds vertically and horizontally within the soil profile (Guérif et al. 2001). However, in no-till systems, weed seeds remain on the soil surface, leaving them exposed to environmental extremes and biological predators (Hoffman et al. 1998; Egley and Williams 1990; Brust and House 1988; Cardina et al. 1996).

Froud-Williams et al. (1981) suggests that conservation tillage systems would select for weeds species such as annual grassy weeds, perennial weeds, volunteer crops as weeds, and wind dispersed species. Likewise, Witt (1984) suggested that these changes in weed populations could be selected by conservation tillage because they allow for early shallow germinating weeds to proliferate in the spring when they would normally be controlled by pre-plant cultivation. A long-term study conducted in Lethbridge, Alberta by Blackshaw et al. (1994) found that dandelion and perennial sowthistle densities increased in minimum and zero tillage treatments. Wruke and Arnold (1985) conducted a study in southeast South Dakota and found that green foxtail (*Setaria viridis*) frequency, density and weed seed yield increased in the no-till treatments. A 4-year study conducted in central Alberta by Malhi et al. (1988) found that perennial grass weeds, such as quackgrass, became a major concern in zero-tillage treatments after 2-3 years. However, weeds with these select life history patterns have not necessarily become a driver weed in western Canada (Derksen et al. 1994). A study conducted by Derksen et al. (1993) at two locations in Saskatchewan suggested that weed communities were influenced more by location and year, rather than tillage regime. Although suggestions of which weed species would increase and decrease after the years of conversion to no-till systems, prairie weed surveys have indicated which species have ultimately changed in abundance and densities (Leeson et al. 2005, 2012; Lesson 2016). A prairie weed survey conducted by Leeson et al. (2005) shows that perennial weeds have been increasing in relative abundance in the prairie provinces since the 1970's. Perennial weeds generally increase in density when tillage operations are removed from the cropping system because tillage acts as a control method for some perennial weeds as it is effective at disrupting the advanced rooting systems of perennial weeds (Koskinen and McWhorter 1986; Lafond and Derksen 1996). For example, foxtail barley (*Hordeum jubatum*) was ranked as the 80th most relative abundant weed in the prairies in the 1980's, whereas in the 2000's it is now ranked as 32nd and still continues to increase in abundance (Leeson et al. 2005). A 12-year study conducted by Brandt (1992) in Scott, Saskatchewan also found that foxtail barley populations increased in the conservation tillage treatments but not conventional tillage treatments.

However, although increases in perennial weed density have been associated with conservation tillage systems, multiple control options are available to producers in most cases. O'Donovan et al. (2001) conducted a study in Vegreville, Alberta that found Canada thistle (*Cirsium arvense*) can be controlled using PRE and/or post-harvest glyphosate, along with POST applications of clopyralid, dicamba and MCPA-K. Similarly, Reidy and Swanton (1994) found that quackgrass could be controlled in corn using various herbicides. Herbicides are available to control weeds in most crops, but there are gaps in control for weeds in certain crops (Derksen et al. 2002). Although glyphosate applied PRE is a common practice among producers who use no-till systems, glyphosate is a non-residual herbicide that is only effective at controlling weeds that have emerged at the time of application.

Foxtail barley is a perennial grass species native to North America (Best et al. 1978). Tillage operations adequately control foxtail barley (Donald 1990), however, pre-plant and post-harvest tillage operations are no longer used in the majority of western Canada due to the adoption of no-till systems. As well, there are limited herbicide control options for foxtail barley, especially in cereal crops (Saskatchewan Ministry of Agriculture 2016).

2.3. Economic Importance

2.3.1. *Detrimental*

Foxtail barley is a perennial grass species native to North America. It occurs in ruderal areas, rangeland and cropland. Foxtail barley is of economic importance to livestock and forage producers because livestock are unable to graze mature plants with seed heads (Best et al. 1978). Late in the year, if livestock do graze on the emerged heads, the barbed awns of the seeds become lodged in the mouths, nostril and eyes of livestock, which can lead to infection (Banting 1979; Blouch 1953; Cords 1960).

Foxtail barley is a source of inoculum of *Septoria avenae* f. sp. *triticea* that can infect wheat and barley (Shearer et al. 1977), as well as head smut (*Ustilago bullata*) (Gossen and Turnbull 1995), barley stripe rust (Brown et al. 1993) and wheat stripe rust (Sanford and Broadfoot 1933). For grain producers, foxtail barley can outcompete crops in soil with a high salinity and moisture concentration (Kenkel et al. 1991; Wilson 1967). A 3-year study conducted by Blackshaw et al. (1998) in Lethbridge, Alberta showed that foxtail barley seedlings ranging in density from 70 to 210 m^{-2} are capable of reducing spring wheat grain yield by 16 to 29% and flax yield by 36 to 52% if left uncontrolled. Donald (1987) reported that foxtail barley can become a problem in no-till or alfalfa (*Medicago sativa* L.) fields in as little as 3 to 4 years. No studies have estimated the economic impact foxtail barley has on western Canadian grain producers because of the weed's inherent variability and gradient-like densities.

2.3.2. *Beneficial*

Foxtail barley can be used as a palatable forage for livestock prior to the formation of heads (Banting 1979; Cords 1960).

2.3.3. *Legislation*

Currently, there no restrictive legislation laws regulating foxtail barley in Canada (CFIA 2017).

2.4. Geographic Distribution

Foxtail barley is present in all provinces in Canada along with all states in the United States with the exception of Florida, Alabama, Mississippi, Louisiana and Hawaii (USDA 2017). Foxtail barley populations in western Canada are becoming more abundant and prevalent. Weed surveys conducted by Lesson et al. (2005, 2016) have showed the gradual spread and increase in abundance of foxtail barley in western Canada since 1976. The increase of foxtail barley abundance in western Canada can be directly linked to the increasing adoption of direct seeding, as well as the ability of the species to colonize multiple environments (Blackshaw et al. 2008; Donald 1990).

2.5. Habitat

2.5.1. *Climatic requirements*

Foxtail barley is well adapted to a wide range of environmental conditions as evident by its dispersal over a broad range of temperate soil and climatic zones including semiarid regions (Best et al. 1978; Dodd and Coupland 1966). Although foxtail barley is commonly found in low elevation saline areas, it can also be found at elevations as high as 3000 m (Best et al. 1978; Wilson 1967). A freeze and thaw stress cycle study conducted by Bolduc et al. (1988) concluded that after five freeze-thaw cycles, 95% of the foxtail barley plants remained alive, whereas only 10 to 50% of the wheat and triticale cultivars tested survived.

2.5.2. *Substratum*

Cropland in western Canada commonly have halophytic areas such as potholes or sloughs that are periodically saturated and have high soil salinity (Dodd and Coupland

1966). Facultative halophytes, such as foxtail barley, commonly establish in potholes, native pasture, riverbeds and seasonal lakes where saline or alkaline habitats and high water tables often occur (Best et al. 1978; Cords 1960; Ungar 2001). Foxtail barley is also commonly one of the first species to colonize disturbed ruderal areas such as roadsides and reclamation sites (Wilson 1967). The ability of foxtail barley to grow in saline conditions allows the plant to be a dominant species in halophytic communities (Badger and Ungar 1989, 1991; Cords 1960; Wilson 1967).

A study conducted by Dodd and Coupland (1966) found that mature foxtail barley plants could survive soil salinities up to 1.5% NaCl, whereas a study conducted by Badger and Ungar (1989) states that mature plants are infrequently found in soils that average above 0.6% NaCl. Moreover, Badger and Ungar (1989) found no significant decline of foxtail barley seedling emergence in salinities up to 2.0%.

2.5.3. (c) *Communities in which the species occurs*

Foxtail barley is a dominant species of halophytic and some ruderal areas. Foxtail barley is often a weed of concern to Alberta county weed inspectors. It is often mowed and spot sprayed multiple times throughout summer to prevent it from encroaching into farmland. However, the weed is most typically found in concentric rings of mixed or pure vegetation stands around potholes (sloughs) (Best et al. 1978).

Dodd and Coupland (1966) conducted a survey of 220 sites in uncultivated saline soils in the grassland zone of Saskatchewan. They found that red swampfire (*Salicornia rubra*), seaside arrowgrass (*Triglochin maritima*), Nuttall's alkaligrass (*Puccinellia airoides)*, saltgrass (*Distichlis stricta*), wheat grass (*Agropyron* spp.) and foxtail barley were the six most dominant plant species in halophytic communities where soil moisture and salinity were fluctuated. The study also found that foxtail barley, wheat grass (*Agropyron* spp.) and Sea-blite (*Suaeda erecta*) were the most commonly associated species within the survey area. The most commonly associated annual species with foxtail barley are Rocky Mountain goosefoot (*Chenopodium salinum*) and salt sandspurry (*Spergularia salina*) (Dodd and Coupland 1966).

Results from a vegetation survey of saline habitats including 45 sites across Saskatchewan and Alberta by Braidek et al. (1984) found that ten species occurred in 25% or more of the surveyed locations: spearscale orache (*Atriplex patula* var. *subspicata*) (31%), kochia (*Kochia scoparia*) (45%), red swampfire (45%), American sea-blite (*Suaeda calceoliformis*) (61%), Heath aster (*Aster ericoides*) (29%), perennial sowthistle (*Sonchus arvensis*) (29%), *saltgrass* (36%), *Nuttall's alkaligrass* (45%), curlycup gumweed (*Grindelia squarrosa*) (25%), and foxtail barley (36%).

Foxtail barley's ability to dominate in these halophytic communities is a result of the plant's salinity tolerance and lack of competition at higher soil salinities (Cords 1960; Wilson 1967). The results of a greenhouse study conducted by Israelsen et al. (2011) found that 519 EC_{days} was needed to achieve 50% biomass reduction (GR_{50}) in foxtail barley, which was greater than other species tested. A greenhouse study conducted by Garthwaite et al. (2005) concluded that salt exclusion was the primary factor responsible for wild *Hordeum* species tolerance to salinity. Moreover, Badger and Ungar (1990b) determined reduced uptake of Na^+ and selective uptake of K^+ was a crucial mechanism of foxtail barley's salinity tolerance, similar to that of Garthwaite et al. (2005).

2.6. Reproduction

2.6.1. *Floral biology*

Seed head emergence begins in the first week of July with the heaviest production occurring in the first 2 weeks but continuing into September (Best et al. 1978). Senescence of the heads begins to occur late July and carries into August dependent on environmental conditions. At maturity, foxtail barley develops nodding seed heads that turn from green to a reddish shiny cream colour. When mature, jointed seed heads ranging from 5-12 cm readily break into seven-bristled clusters consisting of three spikelets (1 fertile and 2 sterile) at each joint with a sharp point, facilitating seed dispersal by wind and animals (Best et al. 1978).

2.6.2. *Seed production and dispersal*

Foxtail barley uses seed production as its primary reproduction strategy (Best et al. 1978). The species is capable of self-fertilization (Babbel and Wain 1977; Best et al. 1978; Comeau et al. 1988; Mulligan and Findlay 1970). The barbed awns of the mature foxtail barley seed aid in its distribution by wind and animals (Best et al. 1978). The long barbed awns of foxtail barley seeds function in multiple ways. The transport of foxtail barley seed by wind and animals allows for foxtail barley seeds to be transported outside its traditional halophytic community (source populations) and into a higher resource environment such as cropland (sink populations). Another feature of the barbed awns of the seed is that once the seed is dispersed in the fall, the awns can prevent the seeds from immediate seed-soil contact, which can inhibit their germination (Badger and Ungar 1989). Typically by the spring, the snowfall from the previous winter has compacted the seeds further into the soil, which can then allow for proper germination (Badger and Ungar 1989). Mature foxtail barley plant seed production ranges from 10 to 300 seeds per plant based on basal size, while 100 seeds per plant is an average production estimate (Best et al. 1978; Van Acker 2009). Seed production estimates from Badger and Ungar (1991, 1994) and Ungar (2001) conclude that a dense foxtail barley population found in a salt marsh of Ohio is capable of producing 15,700 seeds m^{-2}. However, soil salinity in following years of their test area increased, which caused a reduction in seed production down to 500 seeds m^{-2} (Badger and Ungar 1991).

2.6.3. ***Seed banks, seed viability and germination***

Foxtail barley has two primary cohorts of seedling recruitment (Badger and Ungar 1989). The first period is in early August when newly produced seed is shed from the mature plants. The second begins in April and continues throughout the season, however, the peak of the spring seedling recruitment occurs between April and May (Badger and Ungar 1989; Chepil 1946). Seedlings that are recruited in the spring are seeds that have remained viable over the winter period. Badger and Ungar (1989) suggest that the two peaks of germination for foxtail barley are a result of the availability of safe sites for germination in the fall and spring, rather than caused by seed dormancy. Foxtail barley has no primary seed dormancy but secondary dormancy can be induced. Baskin and Baskin (1988) reported that it is uncommon for polycarpic herbaceous species, such as foxtail barley, to have a fall germination period as only 14 of 122 species monitored in their study followed this lifecycle. A study conducted by Badger and Ungar (1994) found that the size of the foxtail barley seed bank populations varied dramatically from one year to the next depending on changes in environmental conditions. Moreover, changes in the seed bank throughout the growing season occur as new seedlings are recruited throughout the growing season (Badger and Ungar 1989). They reported that the seed bank had 3,260 seeds m^{-2} in February and was reduced to 470 seeds m^{-2} by May. Badger and Ungar (1991, 1994) found that the seed bank could have as many as 4,715 foxtail barley seeds m^{-2} before winter in a dense population of foxtail barley. Thompson and Grime (1979) state that because foxtail barley exhibits fall and spring germination periods, it indicates that the species may have a Type III persistent seed bank. Type III seed banks generally have some seeds that germinate soon after release and others which are more persistent in the soil. The continuance of a small persistent seed bank and seedling population from the spring and fall germination periods serves to maintain populations of foxtail barley in habitats that fluctuate in salinity and moisture levels, and where salt stress may increase beyond the tolerance limits of seeds (Badger and Ungar, 1994; Ungar 2001). Foxtail barley's small but persistent seed bank provides it with multiple germination opportunities in unpredictable halophytic or ruderal communities where it is typically located (Badger and Ungar 1994). Ungar and Riehl (1980) and Badger and Ungar (1990a, 1994) state that populations of common glasswort (*Salicornia europaea*), and Spearscale orache (*Atriplex triangularis*) and foxtail barley are commonly found in similar community types, therefore, changes in soil salinity or excess moisture conditions will determine which of these species dominates the area. Badger and Ungar (1994) state that the persistence of foxtail barley seed production coupled with its seed bank and two seedling recruitment periods allows the species to avoid local extinction in zonal communities of their study in extreme environmental situations. In addition, seed dispersal allows for re-colonization of intermittently disturbed ruderal communities.

Halophytic communities adjacent to arable farmland may influence weed communities in the fields and field margins. These halophytic communities often are a seed source distributed into agricultural land leading to the increased abundance of a given weed species (Hume and Archibold 1986). A field study conducted in Saskatchewan by Hume and Archibold (1986) reported that seed rain from grass seed with no wind dispersal from a pasture adjacent to a cultivated field significantly impacted the seed reservoir in the cultivated field. However, the reservoir (seed bank) was only influenced a few meters into the field. Because of wind distribution of foxtail barley seeds, dispersal distances would be longer, although populations decrease with distance. Blumenthal and Jordan (2001) concluded that although the off-site seed reservoir influenced weed dynamics in the margin of a cultivated field, there was little value of controlling the perennial weeds in these areas. Frequent cultivation in the cropping system prevented the establishment of these species further into the cultivated areas (Hume and Archibold 1986; Blumenthal and Jordan 2001). However, this conclusion can be considered from multiple vantage points. In a case where an invasive or problematic weed begins to encroach into farm land, reducing its density and seed in the seed bank is critical to prevent the weed from spreading further into the field. However, managing weeds in the headlands of fields is not always justifiable from an economic standpoint of producers. For example, foxtail barley is often overlooked when producers are making PRE herbicide applications. Producers primarily target driver weeds such as wild oat because they can cause greater yield losses to larger parts of the field. Using targeted tillage to control weeds in headlands is often not utilized because it is both time-consuming and expensive. Furthermore, weeds found in headlands often have large seed bank reservoirs adjacent to the field. Smith and Kadlec (1983) found that when drawdown of a marsh in Utah occurred, foxtail barley and *Tamarix pentandra* were present in the field adjacent to the marsh, however, there was no seeds found in the seed bank of the field, suggesting that the seed source was from the adjacent marsh.

Reports of foxtail barley seed viability vary depending on the seed source and seed position in the soil. Foxtail barley seeds collected from Ontario, Saskatchewan and Alberta by Banting (1979), had greater viability in the short-term (2-3 years) when they remained on the soil surface compared to those that were buried. However, over an extended period of time (7 years), seeds that were buried had greater viability than those on the surface. Furthermore, Banting (1979) and Conn and Deck (1995a) conclude that although foxtail barley seed can remain viable for up to a period of 7 years (1%), viability significantly decreases after 3.7 years.

Reports of seed viability in container storage also vary. Cords (1960) who studied foxtail barley seeds collected from Nevada concluded that viability of foxtail barley seed rapidly declines even under favourable storage conditions. In comparison, seeds collected from Nebraska in a study by Ungar (1974) reported that even after 4 years of storage in favourable conditions, the seeds maintained 96% viability.

Burial depth of foxtail barley seeds impacts both the viability of the seeds as well as germination. Banting (1979) found that foxtail barley seed germination was greater in the top few centimeters of a Regina heavy clay soil, but was much less or absent in a Weyburn loam and Asquith fine sandy soil, except for the seeds on the surface. Likewise, a greenhouse study conducted by Boyd and Van Acker (2003) reported that more foxtail barley seeds germinated from a soil depth of 1-2 cm than surface-placed seeds or seeds buried at 3-4 cm or deeper.

Soil salinity influences seedling germination of halophytes (Glenn et al 1999). Germination of halophytes in saline environments occurs at seasonally low soil salinities (Ungar 1978; Ungar and Riehl 1980). A study conducted by Badger and Ungar (1989) found that foxtail barley seeds were able to germinate in soil salinity concentrations up to 2.0% NaCl. However, sharp reductions in germination percentages were observed at 1.25% NaCl up to 2.0% (Ungar 1974; Badger and Ungar 1989). The germination of over 90.0% in up to 1.0% NaCl solutions as reported by Ungar (1974) explains why foxtail barley is so well adapted to invading moderately saline soils. Germination was not the stage in the lifecycle of foxtail barley that delineates the upper limits of its distribution in saline environments, as the mature plants typically only reproduce in salinities below 1.5% (Ungar 1974, 1978; Badger and Ungar 1989).

Soil moisture concentrations and fluctuations are directly related to fluctuations in soil salinity concentrations; therefore, soil moisture also influences foxtail barley seed germination. Boyd and Van Acker (2003) found that foxtail barley had significantly greater emergence when moisture concentrations fluctuated between field capacity and $1/3^{rd}$ field capacity compared to fluctuating between field capacity and $1/6^{th}$ field capacity. This may help explain why foxtail barley is more commonly found in wet fertile soils (Best et al. 1978).

Temperature, along with salinity-moisture interactions and fluctuations both influence foxtail barley seedling germination. Soil salinity and temperature are often the most significant factors in determining the timing of germination of halophytes (Ungar 1982). Ungar (1982) concluded that the high germination percentages of halophytes in the spring were attributed to reductions in soil salinity and to diurnal fluctuations in temperature. In relation to the fall germination period of foxtail barley, Badger and Ungar (1989) reported that temperature is the predominant environmental factor that delays the germination of foxtail barley. Warm summer temperatures delay the germination of the seeds, but cooler fluctuating temperatures of the fall break the temporary dormancy of the seed and germination begins (Badger and Ungar 1989). The release from dormancy of foxtail barley seed with fluctuating temperatures has also been noted in several greenhouse studies. Ungar (1974) noted that foxtail barley seed had 50% less germination at constant temperatures in comparison with alternating temperatures.

2.6.4. *Vegetative reproduction*

Foxtail barley is a hemicrytophyte (Gates 1940) that has the ability to regenerate from buds in the crown. Mature plants regenerate new shoots every spring when plant growth resumes (Best et al. 1978). Foxtail barley does not regenerate from root stocks, rhizomes or root buds like other perennial grass species (Donald 1990).

2.7. Population Dynamics

Foxtail barley is known for being a dominant species in halophytic communities with high salinity and moisture levels (Best et al. 1978). However, in low-salinity conditions, foxtail barley is a poor competitor against other halophytes such as *Dactylis glomerata* (Wilson 1967). Density-dependent factors can result from both inter- and intraspecific plant competition. Density-dependent factors influence the growth and survival of halophytic species such as *Atriplex prostrate* and foxtail barley (Badger and Ungar 1990a; Keiffer and Ungar 1997). From replacement series experiments, conducted on an Ohio salt marsh, Badger and Ungar (1990a) concluded that *Atriplex triangularis* was capable of reducing foxtail barley root biomass, shoot biomass, and growth rate at multiple stages in its life cycle. This suggested that the competitive interference of *A. triangluaris* at the seedling stage could reduce the later success of foxtail barley (Badger and Ungar 1990a). Kenkel et al. (1991) reported that *Poa pratensis* and *Puccinellia nuttalliana* were able to suppress the growth of foxtail barley depending on soil salinity. A greenhouse study conducted by Wilson (1967) reported that orchard grass (*Dactylis glomerata* L.) provided strong competition to foxtail barley when soil moisture concentrations were elevated. Intraspecific competition of foxtail barley also impacts the species distribution. Keiffer and Ungar (1997) conducted a greenhouse study that concluded intraspecific competition of foxtail barley seedlings and mature plants fluctuated based on the soil salinity concentration that they were grown in. In comparison, although Badger and Ungar (1990a) reported that there are intraspecific factors that influence foxtail barley growth, they concluded that intraspecific competition between the seedlings was not likely to limit the distribution of the species.

2.8. Response to Herbicides and Other Chemicals

2.8.1. *Glyphosate*

Glyphosate [N-(phosphonomethyl)glycine] inhibits EPSP (5-enolpyruvoylshikimate 3-phosphate) synthase, which prevents the synthesis of aromatic amino acids; tryptophan, tyrosine, and phenylalanine, that are essential for plant growth and development (Steinrücken and Amrhein 1980). It is a systemic, non-selective, foliar applied herbicide that was registered in the United States in 1974 (Franz et al. 1997). Glyphosate is classified as a group 9 herbicide in the WSSA- Herbicide Mechanism of Action (MOA) Classification List (WSSA 2017).

Glyphosate is commonly applied PRE in western Canada because it is both effective and economical (Blackshaw et al. 2008). Glyphosates efficacy on foxtail barley has been studied over a range of rates. A study conducted by Donald (1988) in North Dakota reported that a spring application at 390 (g ae ha^{-1}) or lower provided inconsistent control of foxtail barley. Incorporating a non-ionic surfactant at 0.25 % (v/v) with glyphosate at 390 g ha^{-1} provided acceptable control (≥80%) in one of 3 years. Increasing the rate of glyphosate to 560 g ha^{-1} improved the consistency of control at both rating dates spaced 30 days apart. However, glyphosate at 560 g ha^{-1} plus a non-ionic surfactant did not control established foxtail barley in early spring, but adding 2800 g ha^{-1} of ammonium sulfate to the treatment improved the efficacy and consistency of control. A spring application provided good (≥80%) to excellent (≥90%) late season control in all three years at one site, but not at another. The lack of late season control at one of the sites in this study was suggested to be caused by the necrotic tissue of the senesced plants, possibly acting as a barrier for herbicide absorption.

In comparison, Conn and Deck (1995b) conducted a study in Alaska testing two rates of glyphosate (600 or 1100 g ha^{-1}) in combination with 2200 g ha^{-1} of ammonium sulfate and 0.5% (v/v) non-ionic surfactant made at 2-week intervals from May until September on foxtail barley control. Control ratings were conducted in July in the year following application. They reported that the tank mix containing 600 g ha^{-1} of glyphosate resulted in ≤60% control at all application dates. Applications of 1100 g ha^{-1} provided the best control of mature foxtail barley between August and mid-September. However, applications at the same rate made between May and mid-June provided up to 80% control in 1993, but ≤50% in 1992. Similar to that of Donald (1988), Conn and Deck's (1995b) results found that heavy residues resulted in reduced herbicide contact which affects glyphosates uptake by the plant. Lastly, applications of glyphosate at both rates provided poor control (<50%) when applied between June and July when the foxtail barley plants were in their reproductive phase. Therefore, Conn and Deck (1995b) suggest that a fall application of glyphosate at 1100 g ha^{-1} in combination with a surfactant and ammonium sulfate resulted in the best control of mature foxtail barley, which conflicts with Donald (1988) findings.

Blackshaw et al. (1999) findings were similar to that of Conn and Deck (1995b). Blackshaw et al. (1999) conducted a 4-year study in Alberta evaluating the effects of crop row spacing, seeding date, and rate and timing of glyphosate application in a wheat-flax rotation. They reported glyphosate at 400 or 800 g ha^{-1} with ammonium sulfate [3%(v/v)] provided 85 to 100% control of foxtail barley seedlings in a spring application, but only 60 to 70% control of established plants. Although a spring application of glyphosate only suppressed mature foxtail barley plants, biomass and growth rate of the mature plants was reduced, allowing the wheat crop to more strongly compete against the mature weeds. Greater control of mature foxtail barley was achieved when either rate of glyphosate was applied at a fall timing around mid-October. Furthermore, a combination of both spring and fall applications using either rate of glyphosate provided the best control of mature foxtail barley out of all the treatments compared. Blackshaw et al. (1999) concluded that using a multi-application, multi-year approach was a producer's strongest control strategy for successfully managing the weed. Likewise, Tessier et al. (1990) reported that repeat applications of glyphosate were needed in order to control heavy infestations of foxtail barley in their study.

Blackshaw et al. (2000) also examined optimum timing of glyphosate application in the fall to foxtail barley. Preharvest and postharvest applications of glyphosate at 800 g ha^{-1} provided 50 and 70% control of mature foxtail barley in 1994 and 1995, respectively. The lower control in 1994 was likely due to the foxtail barley being drought stressed from reduced precipitation during the growing season. Studies have shown that translocation of glyphosate is reduced in stressed plants, limiting control of large plants (Casely and Coupland 1985; de Ruiter and Meinen 1998). If extended periods of freezing or near-freezing temperature in the fall occur, this may alter a plant's metabolism, therefore potentially reducing herbicide uptake (Ostlie and Howatt 2013). Blackshaw et al. (2000) concluded that although fall applications of glyphosate, or multi-applications (Blackshaw et al. 1999) could adequately control mature foxtail barley plants, the population of foxtail barley was maintained by late emerging foxtail barley seedlings that escaped control of a PRE glyphosate applications. Fall applications of glyphosate to mature plants has little or no effect foxtail barley seeds that emerge following application. Therefore, short residual PRE herbicides, or selective POST herbicides should be assessed for their efficacy on foxtail barley seedling control (Blackshaw et al. 2000).

2.8.2. ***ACCase-inhibitor herbicides***

Group 1, or graminicide herbicides such as quizalofop and sethoxydim inhibit the enzyme Acetyl CoA carboxylase (ACCase), which prevents the production of membrane lipids in plants (Kaundun 2014). The herbicide is absorbed by the foliage and translocated to the meristematic tissue through the phloem, causing leaf tissue development to be stunted and prevents cell division and elongation, which causes plants to become weak and rot (Kaundun 2014).

Currently, there are limited PRE and POST herbicides for the suppression or control of foxtail barley (Saskatchewan Ministry of Agriculture 2016). Quizalofop and sethoxydim are registered in most oilseed and pulse crops for the suppression on foxtail barley prior to seedling tillering. However, Blackshaw et al. (1998) showed that sethoxydim and quizalofop could provide 66 and 97% reductions in foxtail barley biomass when applied at the 1-3 tiller stage in flax, respectively.

Blackshaw et al. (1998) conducted a three-year study in Alberta evaluating tralkoxydim, fenoxaprop, clodinofop, metribuzin and sulfosulfuron applied POST to spring wheat, and sethoxydim, clethodim, quizalofop and fluazifop-P in flax. Tralkoxydim and fenoxaprop did not reduce foxtail barley biomass when applied when foxtail barley was at either the 13-14 or 21-23 BBCH scale of foxtail barley. In flax, quizalofop provided the largest reductions to foxtail barley biomass compared to other herbicides. Quizalopfop applied at the 3-4 leaf stage and 1-3 tiller stage reduced foxtail barley biomass >95% in all cases. However, sethoxydim and clethodim reduced foxtail barley biomass comparable to that of quizalofop when applied at the 3-4 leaf stage, but biomass reductions were less consistent when applied at the 1-3 tiller stage.

2.8.3. *ALS-inhibitor herbicides*

Group 2 herbicides inhibit the biosynthesis of branched-chain amino acids (valine, leucine, and isoleucine) by inhibiting the acetolactate synthase (ALS) enzyme in plants (Ray 1984). ALS inhibiting herbicides are absorbed by both the foliage and roots of the plant, and transported through the xylem and phloem to the growing points where the ALS enzyme activity is high (Peterson et al. 2001). There are five chemical classes of ALS inhibitors: sulfonylurea (SU); imidazolinone (IMI); triazolopyrimidine (TP); pyrimidinyl(thio)benzoate (PTB); and sulfonylaminocarbonyltriazolinone (SCT) (Whaley et al. 2007). There are over 55 active ingredients for Group 2 herbicides, with a wide range of selectivity. Additionally, they have low mammalian toxicity, are applied at low rates and control both grass and broadleaf weeds. Many group 2 herbicides have residual soil activity, which makes them desirable to producers, as this helps control late emerging weeds following application. Unfortunately, this may have consequences to follow crops and increases the selection for group 2 herbicide-resistant weed biotypes (Beckie 2006; Beckie et al. 2008).

2.8.3.1. *Propoxycarbazone-sodium*

Propoxycarbazone-sodium (methyl 2-({[(4-methyl-5-oxo-3-propoxy-4,5-dihydro-1H-1,2,4-triazol-1-y1)carbonyl]amino}sulfonyl)benzoate sodium salt) (hereafter referred to as propoxycarbazone) is a short residual ALS-inhibiting herbicide registered for selective grass control and broadleaf control in wheat, triticale (*Triticosecale rimpaui* Wittm.), and rye (*Secale cereale* L.) in the United States (Geier et al. 2002, Reddy et al. 2013). Propoxycarbazone has efficacy on downy brome (*Bromus tectorum* L.), jointed goat grass (*Aegilops cylindrical* Host), Japanese brome (*Bromus japonicus*), cheat grass (*Bromus secalinus*) and foxtail barley (Geier et al. 2001, 2002; Israelsen 2009; Reddy et al. 2013). Propoxycarbazone's persistence in soil is estimated to have a half-life of 9 days (Herbicide Handbook, 10 ed.). The half-life of a herbicide in soil is the time it takes for 50 % of the chemical to degrade or break down. Characteristics such as soil type, soil pH, organic matter and soil moisture can influence the rate at which the herbicide is degraded in the soil.

Jackson (2007) reported that propoxycarbazone applied at 22 and 44 g ai ha^{-1} provided 95 and 98% biomass reduction, respectively, of seedling and juvenile foxtail barley. This study showed that propoxycarbazone is efficacious on foxtail barley when spring applied, however, the stages of foxtail barley used in this experiment were small in size. The foxtail barley seeds were planted in autumn of 2005, and spring applications of propoxycarbazone were made in the spring of 2006.

Israelsen (2009) conducted a greenhouse dose response on propoxycarbazone control of foxtail barley and pasture grasses in Utah. Foxtail barley seed was collected from an established population and grown in a greenhouse for 6 weeks, then cut to a uniform height. Plants were allowed to recover for 2 weeks, then herbicide was applied 8 weeks after planting. Effective concentration (EC_{50}) 5 and 8 g ha^{-1} (3.5 and 5.6 g ai ha^{-1})

reduced foxtail barley biomass by 50% in replicates 1 and 2, respectively. Similar to that of Jackson (2007), this experiment was conducted on relatively immature plants.

Violett (2012) conducted a study in Wyoming on a mature foxtail barley and reported 60 g ai ha^{-1} propoxycarbazone combined with a non-ionic surfactant (NIS) (0.25% [v/v]) reduced foxtail barley biomass by 59%, and the addition of ammonium sulfate (AMS) (0.25% [v/v]) increased control to 78% biomass reduction. When this study was expanded to a factorial experiment with propoxycarbazone applied alone at 60 g ai ha^{-1} with nitrogen rates of 0, 67 and 135 kg ha^{-1}, control varied from 24%, 43% and 32%, respectively. They concluded NIS and AMS increased propoxycarbazone's efficacy on mature foxtail barley, presumably due to increased uptake. However, a maximum of 31 g ai ha^{-1} of propoxycarbazone is registered for spring wheat in the United States (Anonymous 2006) and the rate tested exceeded the recommended rate.

2.8.3.2. *Flucarbazone-sodium*

Flucarbazone-sodium (4,5-dihydro-3-methoxy-4-methyl-5-oxo-N-[[(trifluoromethoxy)phenyl]-1*H*-1,2,4-triazole 1-carboxamide, sodium salt) (hereafter referred to as flucarbazone) is a short residual POST selective ALS-inhibitor herbicide marketed as Everest 2.0 and Sierra 2.0™ in Canada for wild oat (*Avena fatua*) control in wheat (Saskatchewan Ministry of Agriculture 2016). It also controls green foxtail and broadleaf species such as volunteer canola (*Brassica napus*) (Saskatchewan Ministry of Agriculture 2016). Flucarbazone's persistence in soil is estimated to have a half-life of 17 days (Herbicide Handbook, 10 ed.). Flucarbazone is also pre-formulated with tribenuron-methyl (methyl 2-(((((4-methoxy-6-methyl-1,3,5,-triazin-2-

yl)amino)carbonyl)amino)sulfonyl)benzoate), marketed as Inferno™ Duo in western Canada, registered for a PRE application prior to spring wheat to control dandelions, narrow-leaved hawk's beard (*Crepis tectorum* L.), shepherd's-purse (*Capsela bursa-pastoris*), cow cockle (*Saponaria vaccaria*), and foxtail barley (< 10 cm) when tank-mixed with 450 g ae ha^{-1} of glyphosate. Heavy infestations of foxtail barley or plants greater than 10 cm require Inferno™ Duo plus 900 g ae ha^{-1} of glyphosate for control (Saskatchewan Ministry of Agriculture 2016). However, flucarbazone may injure subsequent legume and oilseed crops in some soils (Szmigielski et al. 2008). A study conducted by Eliason et al. (2004) using six western Canadian soil types reported flucarbazone half-life in the soil ranged from 6 to 110 days and dissipation was influenced by soil organic carbon with rapid dissipation in soils with less organic carbon.

Israelsen (2009) evaluated flucarbazone in a greenhouse dose-response study. He concluded that control of foxtail barley is unlikely to be controlled by flucarbazone at the recommended field rate in the United States of 19.4 g ai ha^{-1} (Anonymous 2008). The EC_{50} for foxtail barley seedlings was 18.5 and 23 g ai ha^{-1}. The Canadian recommended application rate of Inferno™ Duo is 14.6 g ai ha^{-1} (flucarbazone portion) (Saskatchewan Ministry of Agriculture 2016). Therefore, the use of glyphosate with Inferno™ Duo is necessary to achieve control of foxtail barley in a PRE application.

2.8.3.3. *Thiencarbazone-methyl*

Thiencarbazone-methyl (methyl 4-[(4,5-dihydro-3-methoxy-4-methyl-5-oxo-1H-1,2,4-triazol-1-yl)carbonylsulfamoyl]-5-methylthiophene-3-carboxylate), (hereafter referred to as thiencarbazone) is a short residual POST selective ALS-inhibitor herbicide marketed as Varro™ in Canada used for wild oat control in wheat (Kirkland et al. 2001; Saskatchewan Ministry of Agriculture 2016). It also controls barnyard grass (*Echinochloa crus-galli*), green and yellow (*Setaria glauca* L.) foxtail, Japanese brome, as well as other grass and broadleaf species (Saskatchewan Ministry of Agriculture 2016). Similar to that of flucarbazone, thiencarbazone dissipation in Canadian soils varies. Szmigielski et al. (2012) using five Canadian soils in a bioassay estimated the half-life of thiencarbazone at 9 to 50 days. Soil organic carbon and soil pH influenced the dissipation of thiencarbazone. Soils with high organic matter content and low soil pH slows the dissipation of thiencarbazone. Limited information of thiencarbazone's activity on foxtail barley is available.

2.8.4. ***Very long chain fatty acid inhibitor herbicides***

Very long-chain fatty acid (VLCFA) inhibitors are classified as group 15 herbicides (WSSA 2017). They inhibit VLCFA synthesis (Böger et al. 2000). Most group 15 herbicides are applied PRE, however there are a select few products that are applied POST (Senseman 2007). These herbicides inhibit seedling growth; they do not prevent germination of seeds in most cases (Tanetani et al. 2009). When these herbicides are applied to the soil, newly germinated seedlings come into contact with the herbicide. The foliage of the new shoot absorbs the herbicide, leading to seedling death. These herbicides have little to no activity on established weeds (Tanetani et al. 2009).

2.8.4.1. ***Pronamide***

Pronamide or propyzamide (3,5-dichloro-N-(1,1-dimethyl-2-propynl)benzamide), is a group 15 herbicide registered in Canada as Kerb™ for the control of foxtail barley seedlings in grass and grass/legume pasture (Saskatchewan Ministry of Agriculture 2016). Pronamide's persistence in soil is estimated to have a half-life of 18 to 53 days (Herbicide Handbook, 10 ed.). Bowes (1984) conducted a study in Saskatchewan testing propyzamides' activity of foxtail barley seedlings in an established stand of Russian wild ryegrass (*Elymus junceus* Fisch.). Sites were cultivated and seeded to Russian wild ryegrass and spring and fall applications of propyzamide were applied. Bowes (1984) concluded that rates of 0.5 to 1.0 kg ha^{-1} of propyzamide controlled foxtail barley seedlings up to three years if an established stand of Russian wild ryegrass was maintained. However, Bowes (1984) concluded that 100% removal of foxtail barley from the field was highly unlikely as a small number of foxtail barley plants escaped control even when the highest rate of propyzamide was applied. Hamman and Wilson (1977) reported similar results to Bowes (1984) and concluded 0.9 kg ha^{-1} was required to control foxtail barley seedlings in a stand of bromegrass (*Bromus inermis* Leyss.).

2.8.4.2. *Pyroxasulfone*

Pyroxasulfone (3-({[5-(difluoromethoxy)-1-methyl-3-(trifluoromethyl)-1H-pyrazol-4-yl]methyl}sulfonyl)-5,5-dimethyl-4,5-dihydroisoxazole), is a new group 15 herbicide active to western Canada. Pyroxasulfone's persistence in soil is estimated to have a half-life of 16 to 26 days (Herbicide Handbook, 10 ed.). It is currently registered as a pre-formulated herbicide with carfentrazone-ethyl and marketed as Focus® (Saskatchewan Ministry of Agriculture 2016). It is registered for use PRE in field corn, soybean and wheat to control pre-emergent grass and broad leaf species such as green foxtail, downy brome, Japanese brome and cleavers (*Gallium* spp.). The pyroxasulfone component of the product inhibits new seedling establishment of foxtail barley, but does not have activity on established plants (Tanetani et al. 2009). Therefore a tank-mix of Focus® and glyphosate at 450 or 900 g ae ha^{-1} is suggested when using the product. Pyroxasulfone's efficacy is influenced by soil organic matter; increased soil organic matter increases pyroxasulfone's soil binding affinity and therefore decreases its efficacy on weeds (Tidemann et al. 2014; Westra et al. 2014).

A study conducted by Olson et al. (2011) in North Dakota reported pyroxasulfone applied PRE to sunflower (*Helianthus annuus*) at rates of 167, 208 and 333 g ha^{-1} provided 40%, 50% and 75% estimate of visual herbicide control of foxtail barley seedlings, respectively. When pyroxasulfone was tank-mixed with sulfentrazone at a rate of 140 g ha^{-1}, foxtail barley estimates of visual herbicide control improved to 53%, 72% and 72%, respectively.

2.8.5. *Herbicide resistance*

Currently, there are no documented cases of herbicide resistance in foxtail barley biotypes in North America (Heap 2017) and herbicide resistance in perennial plants is less common than for annuals. However, the potential for foxtail barley to develop herbicide resistance is still present, as well as other weed species that may share the same environment. Therefore, herbicide recommendations to control foxtail barley should also take into consideration that herbicides used to control foxtail barley may cause unwanted herbicide resistance development in other weed species.

2.9. Responses to Other Human Manipulations

2.9.1. *Tillage*

Although tillage systems have been gradually replaced by conservation tillage systems in western Canada since the 1980's, tillage is an effective control option for some perennial weeds including foxtail barley. Foxtail barley's shallow-fibrous root system makes it susceptible to tillage operations because the roots are easily disrupted (Donald 1990). Moreover, foxtail barley does not reproduce from root stocks or rhizomes, so tillage operations generally do not facilitate spreading of reproductive organs similar to that of quackgrass (Best et al. 1978; Chandler et al. 1994; Donald 1990). Furthermore, deeper tillage operations using a moldboard or chisel plow inverts the soil, therefore burying foxtail barley seed deep in the soil (Donald 1990). Foxtail barley seed germination is inhibited when seeds are deeper than 7.5 cm in the soil profile (Banting 1979).

Donald (1990) in North Dakota concluded that a fall tillage operation using a moldboard or chisel plow, followed by a spring cultivation-harrow operation effectively controlled established foxtail barley on previously untilled sites before planting spring wheat. However, spring cultivation using a chisel plow followed directly by a cultivation-harrow operation did not achieve full control. Although primary tillage is generally no longer used as a method of weed control in most areas of western Canada, Donald (1990) suggest that occasional shallow tillage operations could be utilized in the spring prior to seeding to aid producers in limiting foxtail barley encroachment onto no-till farmland.

Blackshaw et al. (2000) conducted a study at Champion, Alberta that included tillage treatments as part of his IWM factorial experiment to control foxtail barley in wheat. Tillage treatments consisted of one wide-blade cultivation at a depth of 8-cm in both the fall and spring prior to seeding. The study concluded that tillage had the most consistent effect on foxtail barley growth and wheat yield amongst the other treatments tested. The tillage operations reduced foxtail barley density 3 of 5 years and reduced foxtail barley biomass and seed production in all years of the study. However, the tillage operations were not successful at completely eliminating the foxtail barley population from the study plots.

2.9.2. *Mowing and grazing*

Mowing of foxtail barley is used by producers in some instances when it dominates low saline areas or on roadsides adjacent to crop-land to suppress vegetative growth and seed production. Best et al. (1978) suggest that mowing of mature foxtail barley should occur within 10 days of the initiation of head development. If mowing does not occur within that time frame, viable seeds could be produced and dispersed, although germination may be reduced. Successive mowing may also alter the growth habit of foxtail barley and it may produce seed heads lower to the ground, thus avoiding contact with mower blades (Best et al. 1978).

Livestock grazing prior to the development of heads on mature foxtail barley can reduce foxtail barley vigor and biomass (Best et al. 1978). However, overgrazing or preferential grazing promotes the establishment of foxtail barley by reducing or suppressing desirable vegetation (Best et al. 1978; Bowes 1984; Israelsen et al. 2011).

2.9.3. *Crop seeding rate and row spacing*

A 4 year IWM study conducted by Blackshaw et al. (1999) focused on multiple strategies to control foxtail barley, including increased seeding rates and decreased row spacing of spring wheat and flax. Increasing wheat seedling rate, but not flax, decreased foxtail barley biomass and seed production in year 3 and 4 of the study by 23 and 40%, respectively, and seed production by 39 and 55%, respectively. Narrowing crop row spacing from 30 to 20 cm wide of wheat or flax had little impact on managing foxtail barley.

2.9.4. *Fertilizer placement*

Blackshaw et al. (2000) reported reduced foxtail barley biomass and seed production in some cases when nitrogen was banded, as compared to broadcast in a wheat crop. They reported that foxtail barley is competitive with wheat and canola in low nitrogen soils, but competitiveness with wheat and canola is reduced when soil nitrogen levels are high. This finding also supports the conclusions made in Blackshaw et al. (2003); competitive ability of foxtail barley with wheat and canola may be expected to be reduced at high N fertility levels, but not at low fertility levels.

Potential control options and IWM strategies need to be further researched to provide effective and economic recommendations to producers for controlling foxtail barley. With new PRE and POST herbicide options that have activity on foxtail barley now available in western Canada, a comprehensive herbicide regime can be evaluated for reducing foxtail barley populations. Targeting both the seedling and mature stages of the weed will be crucial in order to be successful at developing an effective strategy.

Chapter Three: Efficacy of Spring-Applied Short Residual ALS and VLCFA-Inhibitor Herbicides in Combination with Glyphosate for Foxtail Barley Control in Spring Wheat

3.1. Introduction

Spring wheat (*Triticum aestivum* L.) is a major annual crop in the Canadian prairies, which was sown on 6.25 million hectares in 2015 (StatsCan 2016). Canadian wheat is in high export demand because of its high quality and protein content (Curtis 2002): 17.9 million tonnes of spring wheat was exported in 2015, making it the highest exported grain commodity in the country (StatsCan 2015). Spring wheat is commonly included in western Canadian crop rotations because of its adaptability in many eco-regions, resilience in unfavourable environmental conditions, and strong competition again weed species (Beres et al. 2010; Iqbal et al. 2016). In Saskatchewan, 46% of producers grow spring wheat 1 in 2 years, and 23% 1 in 3 years (H. Beckie unpubl data). Wheat producers in western Canada face a number of production and marketing challenges, including poor economic returns due to over-supply in the market place, challenging end-use quality standards to achieve in years with lodging, frost damage, weed control, and insect problems (McCallum and DePauw 2008; Beres et al. 2010; McCaig and DePauw 1995).

Prior to the 1980’s, spring wheat in western Canada was produced using a conventional tillage-fallow system. This practice conserved soil water, allowed for a release of soil nitrogen, increased the ease of seeding, and enhanced weed control (Johnson and Ali 1982; Lindwall and Anderson 1981). However, in the face of soil erosion, conservation tillage systems became more widely adopted from the 1980’s onward (Zentner et al. 2002). In the Canadian prairies, 62% of arable land utilizes no-till production systems, and an additional 24% utilize a conservation-tillage management system (StatsCan 2014). New technological advancements and economic advantages such as no-till air seeders and openers, reduced input costs for herbicides, including glyphosate, are among the reasons why no-till production systems have been successfully implemented in western Canada (Collins and Fowler 1996; Gray et al. 1996; Zentner et al. 2002).

Although no-till production systems have been successful at reducing soil erosion and improving soil moisture, a consequence has been a shift in weed species caused by removing primary tillage as a main weed control option (Blackshaw et al. 1994, 2008; Derksen et al. 2002; Moyer et al. 1994; Wruke and Arnold 1985) and the adoption of herbicides as the primary weed control method. A prairie weed survey conducted by Leeson et al. (2005) reported that perennial weeds have been increasing in relative abundance in the prairie provinces since the 1970's. Perennial weeds generally increase in density when tillage operations are removed from the cropping system because tillage acts as a control method for some perennial weeds as it is effective at disrupting the advanced rooting systems of perennial weeds (Koskinen and McWhorter 1986; Lafond and Derksen 1996).

Foxtail barley (*Hordeum jubatum*) is a perennial grass species native to North America (Best et al. 1978). It is a weed in ruderal areas, rangeland and cropland. Foxtail barley is of economic importance to livestock and forage producers because livestock are unable to graze the mature plants once inflorescence has begun (Best et al. 1978). For grain producers, foxtail barley can outcompete crops in soil that has a high salinity and moisture concentration (Kenkel et al. 1991; Wilson 1967). A 3-year study conducted by Blackshaw et al. (1998) in Lethbridge, Alberta showed that foxtail barley seedlings ranging in density from 70 to 210 m^{-2} are capable of reducing spring wheat grain yield by 16 to 29% and flax yield by 36 to 52% if left uncontrolled. Foxtail barley is a highly variable weed species, particularly along ditches, and field edges. The mature plants have a wide range of basal diameters and spatial differences, depending on the environmental conditions and other plant species present in the habitat. Likewise, foxtail barley seedling populations can also be highly variable, depending on the circumstances of seed dispersal and environment at time of release from the mature plants.

Tillage operations adequately control foxtail barley (Donald 1990), however, pre-plant and post-harvest tillage operations are no longer used in the majority of western Canada due to the adoption of no-till systems. Foxtail barley was ranked as the 80th most relative abundant weed in the prairies in the 1980's, whereas in the 2000's it is now ranked as 32nd and still continues to increase in abundance (Leeson et al. 2005).

Glyphosate is commonly used as a pre-seeding (PRE) burndown in western Canada because it is both effective and economical (Blackshaw et al. 2008). Glyphosate's efficacy on foxtail barley has been studied over a range of rates and optimum application timings. Blackshaw et al. (1999) conducted a 4-year study in Alberta evaluating PRE spring application of glyphosate at 400 or 800 g ha^{-1} with ammonium sulfate [3%(v/v)] to control foxtail barley. He concluded that glyphosate at 400 or 800 g ha^{-1} with ammonium sulfate [3%(v/v)] provided 85 to 100% control of foxtail barley seedlings in a spring application, but only 60 to 70% control of the established mature plants. Further studies conducted by Blackshaw et al. (2000) also examined optimum timing of glyphosate application in the fall to foxtail barley. Preharvest and postharvest applications of glyphosate at 800 g ha^{-1} provided 50 and 70% control of mature foxtail barley in 1994 and 1995, respectively. The lower control, reported in 1994, likely due to the foxtail barley being drought stressed from reduced precipitation during the growing season. Studies have shown that translocation of glyphosate is reduced in stressed plants, limiting control of large plants (Casely and Coupland 1985; de Ruiter and Meinen 1998). Furthermore, a combination of both spring and fall applications using either rate of glyphosate provided the best control of mature foxtail barley out of all the treatments compared. Blackshaw et al. (1999) concluded that using a multi-application, multi-year approach was a producer's strongest control strategy for successfully managing the weed. Although split applications of glyphosate were recommended as the optimum control strategy for foxtail barley, the population of foxtail barley was annually perpetuated by late emerging foxtail barley seedlings that escaped control of a PRE application of glyphosate. Therefore, short residual PRE herbicides, or selective post-emergent (POST) herbicides should be assessed for their efficacy on foxtail barley seedling control (Blackshaw et al. 2000).

Currently, there are limited PRE and POST herbicides for the suppression or control of foxtail barley (Saskatchewan Ministry of Agriculture 2016). Pre-formulated Inferno™ Duo (Flucarbazone-sodium + tribenuron-methyl) is registered for PRE application to spring wheat to control foxtail barley up to 10 cm when tank-mixed with glyphosate at 180 g ae ha^{-1}, and for larger or stressed plants, the use of 360 g ae ha^{-1} is required.

Propoxycarbazone-sodium (methyl 2-({[(4-methyl-5-oxo-3-propoxy-4,5-dihydro-1H-1,2,4-triazol-1-y1)carbonyl]amino}sulfonyl)benzoate sodium salt) (hereafter referred to as propoxycarbazone) is a short residual ALS-inhibiting herbicide labeled for selective grass control and broadleaf control in wheat, triticale (*Triticosecale rimpaui* Wittm.), and rye (*Secale cereale* L.) in the United States (Geier et al. 2002, Reddy et al. 2013). Propoxycarbazone is currently being evaluated in western Canada for its efficacy on multiple weeds when applied at a PRE spring timing. Propoxycarbazone has activity on weed grass species such as downy brome (*Bromus tectorum* L.), jointed goat grass (*Aegilops cylindrical* Host), Japanese brome (*Bromus japonicus*), cheat grass (*Bromus secalinus*) and foxtail barley (Geier et al. 2001, 2002; Israelsen 2009; Reddy et al. 2013). Previous studies evaluating propoxycarbazone's efficacy on foxtail barley have varied. Differences in applied rates and stages of the weed may have contributed to conflicting results.

Pyroxasulfone is a new group 15/K_3 herbicide active ingredient to western Canada. The product is currently registered as a pre-formulated herbicide with carfentrazone-ethyl and marketed as Focus® (Saskatchewan Ministry of Agriculture 2016). The product is used PRE in field corn, soybean and wheat to control pre-emergent grass and broad leaf species such as green foxtail, downy brome, Japanese brome and cleavers (*Galium* spp.). The pyroxasulfone component of the product inhibits new seedling establishment of foxtail barley, but does not have activity on established plants.

Therefore a tank-mix of Focus® and glyphosate at 450 or 900 g ae ha^{-1} is suggested when using the product. Pyroxasulfone's efficacy is influenced by soil organic matter; increased soil organic matter increases pyroxasulfone's soil binding affinity and therefore decreases its efficacy on weeds (Tidemann et al. 2014; Westra et al. 2014). A study conducted by Olson et al. (2011) in North Dakota reported that pyroxasulfone applied PRE to sunflower (*Helianthus annuus*) at rates of 167, 208 and 333 g ha^{-1} provided 40%, 50% and 75%control of foxtail barley seedlings, respectively. When pyroxasulfone was tank-mixed with sulfentrazone at a rate of 140 g ha^{-1}, foxtail barley estimates of visual herbicide control improved to 53%, 72% and 72% respectively.

Potential control options and IWM strategies need to be better researched in order to provide effective and economic recommendations to producers for controlling foxtail barley. With new PRE and POST herbicide options that have activity on foxtail barley now available in western Canada, a comprehensive herbicide regime may be evaluated for reducing foxtail barley populations. Targeting both the seedling and mature stages of the weed will be crucial in order to be successful at developing an effective plan.

The objectives of this study were to (1) determine the effective rate of glyphosate required to control foxtail barley in a pre-seeding application, (2) determine if tank-mixing a short residual herbicide applied PRE with glyphosate increases foxtail barley control, (3) determine if the efficacy of the short residual herbicides varies on foxtail barley control (4) determine if tank-mixing two residual products with glyphosate provides greater control of foxtail barley than compared to one residual herbicide, and (5) determine if incorporating a PRE application of glyphosate and a short residual herbicide followed by a POST application of a short residual herbicide improves foxtail barley control.

3.2. Materials and Methods

3.2.1. Field Experiments

Two studies were conducted at 6 sites: Lethbridge in 2015 and 2016, Olds, AB and Scott, SK in 2015, and Vermilion and St. Albert, AB in 2016 (Table 3-1). Trials were established on no-till agricultural crop-land naturally infested with moderate to dense populations of foxtail barley (Table 3-1). Scott had uniform populations while the remaining sites had higher densities closer to the seed source (headland areas), therefore, replicates were placed parallel to population densities, maintaining a uniform population in each replicate as possible. Previous years stubble type varied by site. A pre-seeding application of florasulam at 4.94 g ai ha^{-1} was applied at Lethbridge 2015-2016, Scott and St. Albert prior to the studies' herbicide treatments being applied to remove potentially confounding broadleaf weed species. AC Harvest hard red spring wheat was sown at a depth of 3 cm and a rate of 350 seeds m^{-2} between the dates of April 29th to May 22nd at all sites using a no-till Fabro plot seeder with Atom jet openers spaced at 20 cm. Each site was fertilized with urea, monoammonium phosphate and ammonium sulfate as per soil test recommendations to achieve a wheat seed yield of 2700 kg ha^{-1}. Sowing of the sites occurred one week following the PRE herbicide treatments application (Table 3-2). Precipitation was monitored during the growing season (Table 3-3).

3.2.2. Experimental Design

Experiments were arranged in a randomized complete block design with four replicates. Plots were 2 m wide and 7.5 m long at all sites except Scott (5.5 m). Study 1 consisted of 4 PRE short residual herbicide treatments: propoxycarbazone-sodium at 7.5 and 10 g ai ha^{-1} (Olympus®- Bayer CropScience, Research Triangle Park, NC), flucarbazone-sodium/tribenuron-methyl at 21.79 g ai ha^{-1} (Inferno Duo®- Arysta, Cary, NC, USA), and pyroxasulfone at 150 g ai ha^{-1} (Zidua®- BASF, Florham Park, NJ, USA)) applied alone, and in combination with 2 rates of glyphosate, 450 and 900 g ae ha^{-1}, (Roundup Weathermax®- Monsanto, St. Louis, MO, USA). Study 2 consisted of 12 treatments with a PRE base application rate of glyphosate at 900 g ae ha^{-1} applied with various combinations of the 3 residual products and a POST application of thiencarbazone-methyl at a rate of 4.94 g ai ha^{-1} (Varro®- Bayer CropScience, Research Triangle Park, NC). As per label recommendations, 2% (v/v) ammonium sulfate at a rate of 1.24 l ha^{-1} was added to thiencarbazone-methyl. Refer to Figure 3-1 for complete treatment description. Both studies included a non-treated control (NTC). Study 1 and 2 PRE herbicide treatments were applied early in the spring when mature foxtail barley was initiating new shoot growth and seedling emergence (Table 3-2). POST herbicide treatments were applied at the 4 leaf wheat stage (Table 2). All herbicide treatments were applied with a CO_2 -pressurized hand-boom sprayer calibrated to apply 100 l ha^{-1} at 380 kPa. The spray boom was 1.5 m wide with four ABJ ORANGE 0.1 nozzles spaced 50 cm apart.

3.2.3. Data Collection

Soil moisture was collected volumetrically (%) throughout the growing season at each site**.** Mature foxtail barley plants were initially quantified at each site using 20, 0.25

m^{-2} quadrat counts per trial prior to PRE herbicide treatments being applied. Visual estimates of herbicide control on foxtail barley were made on a scale of 0% (no control) to 100% (complete plant death) at 7, 21 and 28 days after treatment (DAT) application for both PRE and POST treatments. Foxtail barley seedling density was quantified in one 0.5 m^2 quadrat placed 1 m from the back of each plot. Emergence seedlings of foxtail barley were marked weekly with avian leg bands and survivors counted 14, 21 and 28 DAT to evaluate the herbicides efficacy on inhibiting foxtail barley seedling germination (Scott, SK data not included). Twenty-one days prior to harvest, foxtail barley (shoots and seedlings) and wheat (shoots and inflorescence) were cut at the soil surface from one 0.25 m^2 quadrat per plot and plants were separated by species. Plant biomass was dried at 50 °C to a constant moisture for 5 to 7 days and weighed to determine shoot dry mass. Plots were harvested when the crop reached grain moisture content <14%, BBCH 89 stage, to determine crop seed yield. Wintersteiger plot-harvesting combines were used at each location, harvest width being 1.8 m, for the entire length of the plot. Crop seed samples were cleaned and weighed. Fifteen soil samples were randomly collected from the test area then bulked for analysis to determine soil texture, OM, pH and EC.

3.2.4. Statistical analyses

Statistical analysis was performed using lme4 in R 3.3.1 (R Core Team (2016). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/). All data were checked for homogeneity of variance before statistical analysis by plotting residuals. Site was analyzed as a fixed effect, and was not significant at $P \geq 0.05$, except for visual estimates of herbicide control where sites were analyzed separately in two groups. Therefore, for remaining data sites were pooled for analysis. Herbicide treatment was designated as a fixed effect, and site was considered random. No significant interactions between herbicide treatments were observed for trial 2 wheat biomass and seed yield at $P \geq 0.05$. When herbicide treatment was found to be significant ($P \leq 0.05$), means were separated using Tukey method. Pre-planned non-orthogonal contrasts were used to analyze combinations of residual herbicides in study 1 and adjusted using a Bonferroni correction factor.

3.3 Results and Discussion

3.3.1. Growing Season Weather

Annual observed precipitation varied among sites and years. Lethbridge 2015 received 58% of the growing season rainfall long-term average (GSR LTA) while Scott and Lethbridge 2016 received 82% and 84%. Olds, Vermillion and St. Albert received normal precipitation during the growing season. Precipitation before product application also varied (Table 3-1). Lethbridge 2015-2016 and Scott received substantially lower rainfall prior to typical PRE herbicide application timing with only 6, 43 and 13% rainfall received of the long-term average, respectively. In contrast, Olds, Vermilion and St. Albert received close to, or above the long term average with 74, 76 and 266% rain received compared to the long-term average, respectively. Differences in cumulated rainfall between sites is a key factor that determines foxtail barley population growth and vigor throughout the growing season. Blackshaw et al. 1998, 1999 also found a similar trend in their studies. Average temperatures were recorded at each site for the growing season (data not shown). Seeding and product application dates were applied at typical timings appropriate for the location (Table 3-2). Soil OM, pH and EC were not found to influence efficacy of the herbicides tested in these experiments. Trials were located on non-saline sites, therefore we do not anticipate that EC influenced crop seed yield.

3.3.2. Trial 1- Evaluation of short residual herbicides in combination with varying rates of glyphosate

This trial was designed to compared the effects of glyphosate on foxtail barley when applied PRE, alone, and tank-mixed with short residual ALS and VLCFA herbicides.

3.3.2.1. Visual Estimates of Herbicide Control

Foxtail barley densities differed among sites (Table 3-1). Data for visual estimates of herbicide control were grouped for analysis based on foxtail barley population densities at each site. Foxtail barley density was the primary reason for the site groupings, however environmental conditions throughout the growing season also reinforced the site groupings based on responses by the foxtail barley plants, and how the herbicides responded at each site. The average foxtail barley density across Lethbridge 2015, Vermilion and St. Albert was 28.3 mature plants and 38.3 seedlings m^{-2}, whereas the average plant density across Lethbridge 2016, Olds and Scott was 45.7 mature plants and 19.7 seedlings m^{-2}. Therefore, the ratios of mature plants to seedlings differed among the site groups.

Foxtail barley control was greater in Lethbridge 2015, Vermilion and St. Albert where there was a lower density of mature plants, and lower control in Lethbridge 2016, Olds and Scott where mature foxtail density was high (Figure 3-1). Control with glyphosate at 450 g ae ha^{-1} averaged 42.4 and 63.5% at the Lethbridge 2016, Olds, Scott and Lethbridge 2015, Vermilion, St. Albert, respectively and at 900 g ae ha^{-1} visual estimates of herbicide control reached 72.7 and 84.8%, respectively. Both low and high rate of glyphosate provided significant ($P < 0.0008$) control compared to non-treated check (NTC) in both density groups, and the high rate of glyphosate provided significant increases in control compared to the low rate ($P < 0.0008$). In Lethbridge 2015, Vermilion and St. Albert, the treatment with the high rate of propoxycarbazone (10 g ai ha^{-1}) tank-mixed with glyphosate at the low or high rate provided significant increase in control compared to glyphosate applied alone ($P < 0.0056$), which did not occur at Lethbridge 2016, Olds or Scott ($P < 0.3072$). This likely occurred because of the higher density of mature plants at these sites. Tank-mixes of the low rate of propoxycarbazone (7.5 g ai ha^{-1}), flucarbazone/tribenuron or pyroxasulfone in combination with glyphosate did not significantly improve foxtail barley control.

3.3.2.2. Seedling Recruitment

Treatments containing pyroxasulfone significantly reduced seedling recruitment compared to the NTC after application ($P < 0.0088$) (Figure 3-2). Pyroxasulfone tank-mixed with low and high rate of glyphosate reduced seedling recruitment to 5.78 (83.7% reduction) and 4.23 (88.1% reduction) seedlings m^2, respectively, while the NTC had 35.56 seedlings m^2. Pyroxasulfone performed exceptionally well at St. Albert although the soil OM was 11.5%. This site also had a large amount of rainfall (Table 3-3) occur at the time of PRE herbicide application, which we believe resulted in the increased uptake of pyroxasulfone by the foxtail barley plants. Adding a short residual product to glyphosate tended to reduce seedling emergence (Figure 3-3) although not significantly. Pyroxasulfone provided similar reduced seedling recruitment as other short residual products. Glyphosate applied alone did not reduce foxtail barley seedling recruitment when compared to the NTC. Results from Blackshaw et al. 1999 show similar results that glyphosate alone applied PRE provides 85-100% visual control of newly emerged foxtail barley seedlings.

3.3.2.3. Foxtail Barley Biomass

Both the low and high rate of glyphosate applied alone provided significantly greater foxtail barley biomass reductions than the NTC ($P < 0.0008$) (Figure 3-3). The high rate of glyphosate provided an 83.7% reduction in foxtail barley biomass, whereas the low rate provided a 70.3% reduction compared to the NTC. While they were not significantly different, a trend can be observed that increasing the rate of glyphosate can reduce foxtail barley biomass. Likewise, the addition of residual products to glyphosate tended to increase foxtail barley control compared to glyphosate applied alone. For example, pyroxasulfone tank-mixed with the high rate of glyphosate decreased foxtail barley biomass by 13.9% in compared with high rate of glyphosate applied alone. The short residual products applied in the absence of glyphosate do not significantly reduce foxtail barley biomass, and should not be recommended for use to control foxtail barley without being tank-mixed with glyphosate. Results from Blackshaw et al. 1999 correspond to the results found in this study. Blackshaw et al. 1999 found that 400 g ae ha^{-1} of glyphosate applied PRE provided 54.3% reduction in foxtail barley biomass, and

800 g ae ha^{-1} provided 81.9% reduction in biomass.

An observation was made during these experiments that glyphosate applied alone at the low rate struggled to control mature foxtail barley when the plants were under drought or excessive moisture stress. Glyphosate translocation in plants can be reduced when they are stressed, which results in reduced control of the weed (Casely and Coupland 1985; de Ruiter and Meinen 1998; Ostlie and Howatt 2013). A reduction of control was not apparent when the high rate of glyphosate was applied. Therefore, an argument could be made that applying 900 g ae ha^{-1} of glyphosate compared to 450 g ae ha^{-1} to control mature foxtail barley is justifiable when controlling stressed mature plants. Furthermore, a second mode of action tank-mixed with glyphosate at 900 g ae ha^{-1} may potentially provide additional control to healthy or stressed mature foxtail barley plants.

3.3.2.4. Spring Wheat biomass

Both the low and high rate glyphosate treatments provided significantly greater wheat biomass compared to the NTC (P = 0.0080, P = 0.0200, respectively) (Figure 3-4). The high rate of glyphosate was not more effective than the low rate glyphosate. No treatments that included a short residual product tank-mixed with glyphosate at either the low or high rate of glyphosate provided a significant increase in wheat biomass compared to glyphosate applied alone. However, a trend can be observed that the high rate of glyphosate increased wheat biomass compared to the low rate. Likewise, applying a residual product in combination with glyphosate can provided increased wheat biomass compared to glyphosate applied alone. This trend is likely the result of improved foxtail barley control or other weed species that are controlled by these ALS and VLCFA-inhibitor herbicides. No residual herbicide treatments differed from another.

3.3.2.5 Spring Wheat Seed Yield

The high rate of glyphosate provided significantly greater wheat seed yield compared to the NTC ($P < 0.0048$), whereas the low rate of glyphosate did not ($P < 0.2160$) (Figure 3-5). The high rate of glyphosate did not provide significantly greater wheat seed yield compared to the low rate of glyphosate. However, the high rate of glyphosate increased wheat seed yield by 20 g m^{-2} (3 bu ac^{-1}) compared to the low. No residual products tank-mixed with glyphosate at either the low or high rate provided significantly greater wheat seed yield versus glyphosate applied alone. However, a trend can be observed that adding a residual product in combination to glyphosate does increase average wheat seed yield. For example, when propoxycarbazone at 7.5 and 10 g ai ha^{-1} and pyroxasulfone were each tank-mixed with the low rate of glyphosate, they significantly increased wheat seed yield compared to the NTC, whereas glyphosate applied alone did not. Likewise, flucarbazone/tribenuron tank-mixed with the high rate of glyphosate increased weed seed yield by 18.3 g m^{-2} compared to the high rate of glyphosate applied alone. No treatments containing residual herbicides significantly performed better than another. Results from Blackshaw et al. 1999 do not correspond to the results found in this study. Blackshaw et al. 1999 found that 400 g ae ha^{-1} of glyphosate applied PRE provided 210% and 257% increase in spring wheat seed yield when 400 and 800 g ae ha^{-1} was applied PRE.

3.3.3. Trial 2- Evaluation of multiple short residual PRE and POST herbicides in combination with glyphosate

This trial was designed to evaluate optimal PRE and POST short residual herbicide tank-mix regimes with a standard rate of glyphosate for foxtail barley control.

3.3.3.1. Visual Estimates of Herbicide Control

Scott and St. Albert (1); and Lethbridge 2016 and Vermilion (2) were grouped for analysis based on foxtail barley density present at the sites. Mature foxtail barley density at Scott was greater than all other sites (76 plants m^{-2}). Similarly St. Albert had the greatest seedling population (81 seedlings m^{-2}), whereas Lethbridge 2016 and Vermilion had average densities of both mature and seedling plants (Table 3-1). Foxtail barley density was the primary reason for the site groupings, however environmental conditions throughout the growing season also reinforced the site groupings based on responses by the foxtail barley plants, and how the herbicides responded at each site. The analysis of Olds and Lethbridge 2015 are not presented because weed control from pre-seeding applications was very high and there were no significant differences between in crop herbicides treatments at either site. The two site groups responded similarly, however, we observed greater foxtail barley control at our Lethbridge 2016 and Vermilion sites compared to Scott and St. Albert. The reduction in control at Scott and St. Albert was likely a result of greater cumulative seedling recruitment at these sites (Table 3-4). Tank-mixing the high rate of propoxycarbazone and glyphosate followed by a POST application of thiencarbazone provided significantly greater control of foxtail barley compared to glyphosate applied alone ($P < 0.0008$, $P < 0.0001$) (Figure 3-6). Similarly, glyphosate tank-mixed with the high rate of propoxycarbazone and pyroxasulfone followed by a POST application of thiencarbazone provided significantly greater control compared to glyphosate applied alone at all 4 sites ($P < 0.0064$, $P < 0.0001$). Other treatments with a single PRE herbicide application, or a tank-mix with the low rate of propoxycarbazone and glyphosate applied PRE followed by a POST application of thiencarbazone did not provide significantly greater control over glyphosate applied alone.

3.3.3.2 Foxtail Barley Biomass

Three treatments containing residual herbicides were able to reduce foxtail barley biomass compared to glyphosate applied alone. Glyphosate tank-mixed with combinations of flucarbazone/ tribenuron and pyroxasulfone applied PRE ($P < 0.0001$) (1); propoxycarbazone (7.5 g ai ha^{-1}) and pyroxasulfone applied PRE followed by thiencarbazone applied POST ($P < 0.0001$) (2); and propoxycarbazone (10 g ai ha^{-1}) and pyroxasulfone applied PRE followed by thiencarbazone applied POST ($P < 0.0008$) (3) reduced biomass compared to glyphosate applied alone (Figure 3-7). Biomass averaged 2.82 (90.2% reduction), 2.53 (91.2% reduction) and 4.53 g m^{-2}, respectively, compared to 28.67 (84.2% reduction) g m^{-2} when glyphosate was applied alone. They targeted both the mature and seedling plants at two different application timings. But they were equivalent to tank-mixes of a residual product with glyphosate at a PRE timing. No treatments in trial 1 or 2 eliminated foxtail barley plants from the plots. A few foxtail barley plants were always able to survive the herbicide treatments, potentially leading to the reestablishment of the population. In Blackshaw et al. 1998, MON37500 reduced foxtail barley biomass by 94.5% when applied at 20 g ai ha^{-1} POST to 3-4 leaf foxtail barley in wheat. MON37500 was less effective at reducing foxtail barley biomass when the herbicide was applied at the one-three tiller stage, reducing foxtail barley biomass by 86.3%. Thiencarabzone applied alone to foxtail barley at either stage is unlikely to reduce foxtail barley biomass to the same degree as MON37500, but more testing of thiencarbazone applied to mature foxtail barley plants is required to test this hypothesis.

3.3.3.3. Spring Wheat Biomass and Yield

No treatments containing a PRE or POST herbicide application significantly increased wheat biomass or wheat seed yield greater than 900 g ae ha^{-1} of glyphosate applied alone (Figure 3-8 and 3-9). The high rate of glyphosate applied PRE is sufficient to protect crop yield. However, Blackshaw et al. 1999 concludes that two applications of 800 g ae ha^{-1} of glyphosate PRE and post-harvest are required to protect crop yield.

3.4. Conclusion

Foxtail barley natural populations assessed under environmental conditions in Alberta and Saskatchewan were variable in density and the proportion of growth stages because of the population origins; usually seed dispersed from roadsides or adjacent saline areas. As a result, data was more variable than for experiments conducted on uniform populations of annual weeds. Data from six widely distributed sites conducted over two years allows for a conservative conclusion to be reached.

In trial 1, the estimates of visual herbicide control showed that the high rate of glyphosate resulted in greater estimates of visual herbicide control of foxtail barley, but not in biomass reductions compared to the low rate. However, results from Blackshaw et al. 1999 contradict this finding, suggesting that 800 g ae ha^{-1} of glyphosate provides greater foxtail barley biomass reductions compared to 400 g ae ha^{-1}. The high rate of propoxycarbazone tank-mixed with glyphosate was the only treatment that provided significantly increased control over glyphosate applied alone at sites that had more seedling and few mature plants. Tank-mixing a residual product with glyphosate typically increased foxtail barley control, however efficacy of the residual products provided similar estimations of visual herbicide control of foxtail barley.

In trial 2, a tank-mix of the high rate of propoxycarbazone and glyphosate followed by a POST application of thiencarbazone, as well as a tank-mix of glyphosate, propoxycarbazone and pyroxasulfone followed by thiencarbazone provided significantly increased estimates of visual herbicide control compared to glyphosate applied alone. However, only the tank-mix of glyphosate, propoxycarbazone and pyroxasulfone followed by thiencarbazone significantly reduced foxtail barley biomass.

Treatments containing pyroxasulfone were the only treatments that significantly decreased seedling recruitment compared to glyphosate applied alone. Although propoxycarbazone and flucarbazone/tribenuron did not provide significant reductions in foxtail barley seedling recruitment, they did reduce recruitment to some degree. Pyroxasulfone did not significantly provide greater foxtail barley seedling reductions in comparison to the other ALS residual herbicides used in this study. This finding suggests that pyroxasulfone provides greater foxtail barley seedling control than glyphosate, however, pyroxasulfone was equivalent to the ALS-inhibitor herbicides.

While we observed a trend that increasing the rate of glyphosate applied PRE does increase wheat biomass and wheat seed yield, no treatments were significantly greater than a PRE application of glyphosate at 450 g ae ha^{-1}.

The results of this study suggest that tank-mixing a PRE short residual herbicide to glyphosate at a rate of 900 g ai ha^{-1} followed by a POST emergent herbicide with activity on foxtail barley would be the optimum herbicide regime to reduce foxtail barley populations in spring wheat. However, seedling emergence was observed over an extended period in spring and post-harvest, suggesting that pre-seeding, post-emergent and post-harvest control timings along with a multiyear IWM strategy may be required to maintain foxtail barley populations at low densities. Due to the re-infestation of foxtail from roadsides and waste areas, eradication of foxtail barley from fields is unlikely. One way to reduce herbicide costs and environmental impacts would be to applied herbicides only to the field edges where foxtail barley is encroaching. Other IWM strategies such as targeted tillage in field edges, along with the use of ACCase-inhibitor herbicides in broadleaf crops in other years would help producers minimize foxtail barley reintroduction into non-infested areas. While it may be cost effective in the short term, due to concerns with selection of herbicide resistance with glyphosate (Gaines et al. 2016; Wiersma et al. 2015), we cannot recommend consistent applications of glyphosate alone.

Table 3-1 Plant population and soil characteristics for each location including soil type, percent composition of sand, silt, clay, and organic matter (OM)[a], soil pH[b] as well as soil EC.

Year	Location	Mature (m^{-2})	SE	Seedlings (m^{-2})	SE	Soil texture	Sand	Silt	Clay	OM	Soil pH	EC (mS/cm)
							--------------%-----------					
2015	Lethbridge	44	6.6	10	1.5	Sandy clay loam	54.1	18.7	27.2	2.7	7.8	0.3
	Olds	28	2.8	32	4.8	Loam	35.8	40.2	24.0	8.0	6.0	0.5
	Scott	76	3.8	14	0.7	Loam	36.4	47.4	16.2	2.8	5.8	0.1
2016	Lethbridge	33	5.0	13	1.3	Sandy clay loam	65.8	12.2	22.0	2.9	7.9	0.5
	Vermilion	17	2.6	24	2.4	Sandy loam	68.6	20.7	10.7	5.5	7.2	0.34
	St. Albert	24	2.4	81	4.1	Silty clay	14.0	43.1	42.9	11.5	6.5	0.85

[a] Abbreviations: OM, organic material; EC, electrical conductivity.

[b] Soil characteristics taken at 0-15 cm depth.

[c] Lethbridge 2016 different field location than 2015.

Table 3-2 Dates of wheat planting, PRE and POST applications.

Year	Location	PRE [a] application	Planting date	POST application
2015	Lethbridge	April 27	May 4	June 9
	Olds	May 5	May 12	June 10
	Scott	May 15	May 22	June 25
2016	Lethbridge	April 22	April 29	June 10
	Vermilion	May 10	May 17	June 13
	St. Albert	May 12	May 19	June 23

[a] Abbreviations: PRE, pre-emergence; POST, post-emergence.

Table 3-3 Summary of precipitation during growing season and PRE application, and soil moisture at PRE application at all sites in 2015 and 2016.

		Precipitation						
Year	Location	GSR[a]	GSR LTA	% of GSR LTA	APPR[b]	APPR LTA	% of APPR LTA	Soil moisture[c]
		------mm------		--------%-------	--------mm----------		--------%--------	Vol. (%)
2015	Lethbridge	172	298	58	2	31	6	22.0
	Olds	395	386	102	26	35	74	29.2
	Scott	240	291	82	4	32	13	15.7
2016	Lethbridge	249	298	84	13	30	43	18.3
	Vermilion	363	325	112	22	29	76	9.7
	St. Albert	375	349	107	77	29	266	20.1

[a] Abbreviations: PRE, pre-emergence; GSR, growing season (April-October) rainfall; LTA, long-term average (30 years); APPR, rainfall prior to application.

[b] Application rainfall window: 3 week period (1 week preceeding-2 weeks following PRE application)

[c] Soil moisture on date of PRE application

Table 3-4 Cumulative seedling recruitment expressed as density and percent of cumulative emergence, 28 days after POST application. Emergence was assessed in untreated plots.

Year	Site	Date	Cumulative seedlings recruitment (m^{-2})	Cumulative (%) spring seedling recruitment
2015	Lethbridge	July 7	19	9
	Olds	July 8	437	62
	Scott	July 23	128	70
2016	Lethbridge	July 8	101	33
	Vermilion	July 11	37	52
	St. Albert	July 21	202	51

Abbreviations: POST, post-emergence

Table 3-5 ANOVA: Trial 1 Visual estimate of herbicide control- Lethbridge 2016, Olds, Scott

	F value	Df	Df.Res	Pr (>F)
(Intercept)	0.0018	1	59.8810	0.9660
TRT	43.3179	14	148.0030	<2e-16

Table 3-6 ANOVA: Trial 1 Visual estimate of herbicide control- Lethbridge 2015, Vermilion, St. Albert

	F value	Df	Df.Res	Pr (>F)
(Intercept)	0.0008	1	71.9090	0.9779
TRT	124.6789	14	148.0050	<2e-16

Table 3-7 ANOVA: Trial 1 Seedling recruitment

	F value	Df	Df.Res	Pr (>F)
(Intercept)	7.7003	1	8.7810	0.0220
TRT	1.5553	14	251.0000	0.0924

Table 3-8 ANOVA: Trial 1 Foxtail barley biomass

	F value	Df	Df.Res	Pr (>F)
(Intercept)	105.9600	1	43.4650	3.14e-13
TRT	12.2990	14	312.0110	<2.2e-16

Table 3-9 ANOVA: Trial 1 Spring wheat biomass

	F value	Df	Df.Res	Pr (>F)
(Intercept)	6.9175	1	5.7100	0.0409
TRT	3.7060	14	312.0000	9.31e-06

Table 3-10 ANOVA: Trial 1 Spring wheat seed yield

	F value	Df	Df.Res	Pr (>F)
(Intercept)	7.5673	1	5.3680	0.0373
TRT	3.6409	14	312.0000	1.26e-05

Table 3-11 ANOVA: Trial 2 Visual estimate of herbicide control- Scott & St. Albert

	F value	Df	Df.Res	Pr (>F)
(Intercept)	39.4530	1	1.4980	0.0929
TRT	4.0229	11	83.0000	0.0001

Table 3-12 ANOVA: Trial 2 Visual estimate of herbicide control- Lethbridge 2016 & Vermilion

	F value	Df	Df.Res	Pr (>F)
(Intercept)	2.89e+30	1	1.4980	1.0000
TRT	3.30e+35	11	83.0000	1.0000

Table 3-13 ANOVA: Trial 2 Visual estimate of herbicide control- Lethbridge 2015 & Olds

	F value	Df	Df.Res	Pr (>F)
(Intercept)	3.30e+35	1	90.0000	1.0000
TRT	3.30e+35	11	90.0000	1.0000

Table 3-14 ANOVA: Trial 2 Foxtail barley biomass

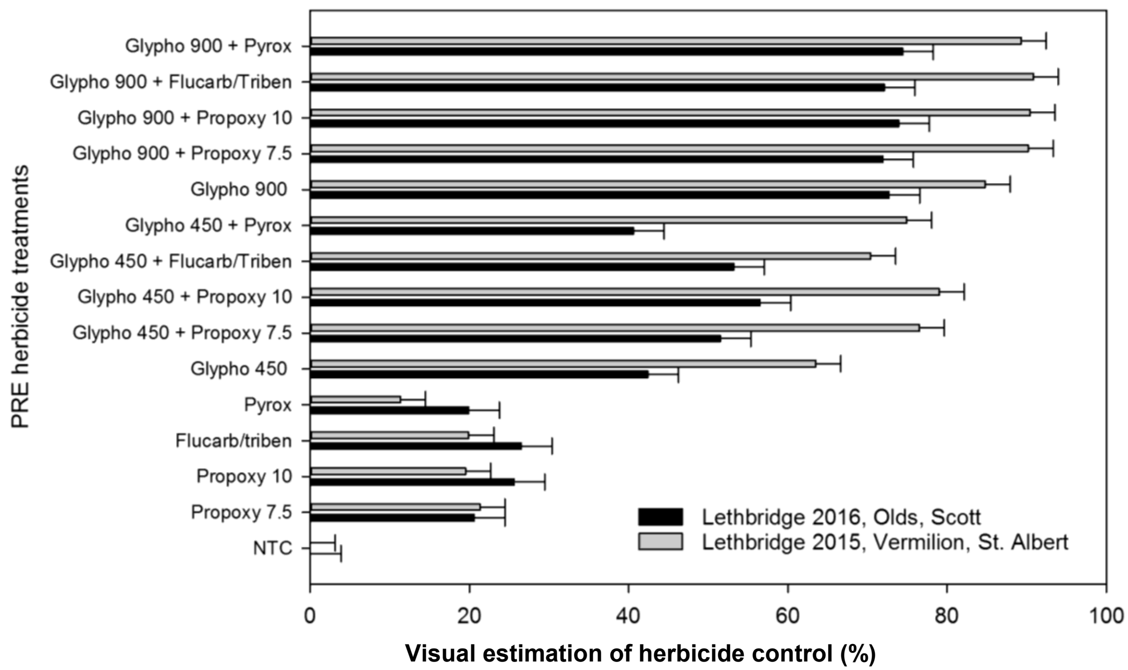
	F value	Df	Df.Res	Pr (>F)
(Intercept)	23.2379	1	23.1750	0.0001
TRT	2.9875	11	247.0010	0.0009

Table 3-15 ANOVA: Trial 2 Spring wheat biomass

	F value	Df	Df.Res	Pr (>F)
(Intercept)	9.9208	1	5.3780	0.0230
TRT	2.9875	11	247.0000	0.6625

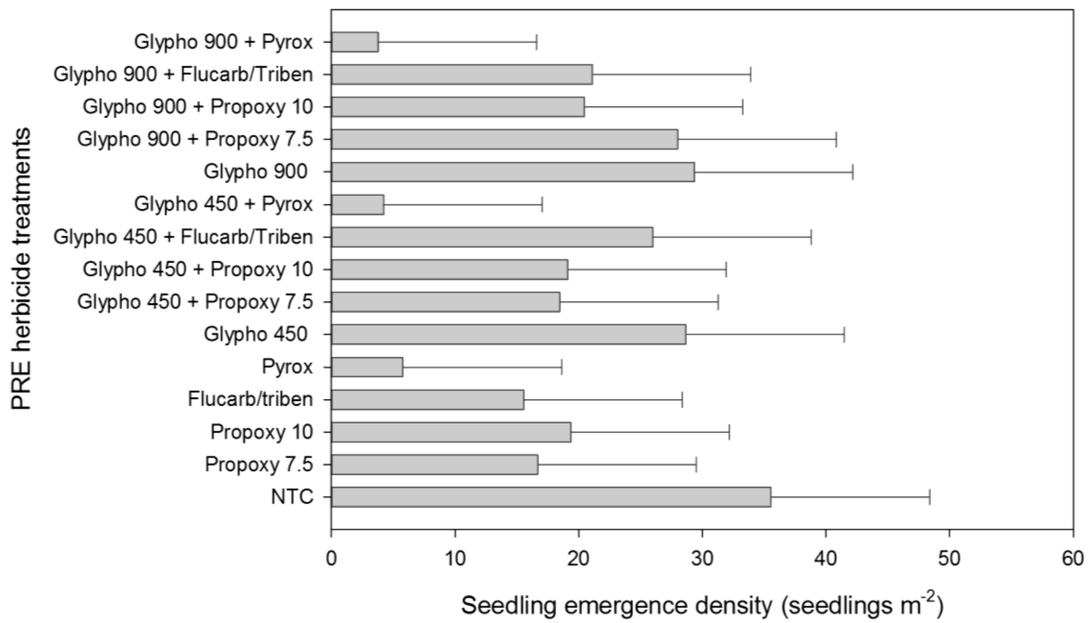
Table 3-16 ANOVA: Trial 2 Spring wheat seed yield

	F value	Df	Df.Res	Pr (>F)
(Intercept)	10.0960	1	5.1840	0.0234
TRT	0.8750	11	247.0000	0.5655



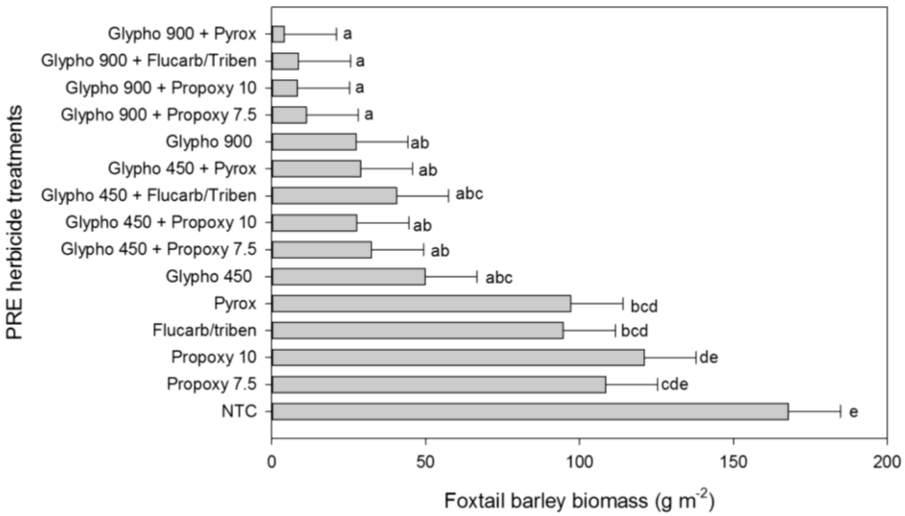
	Lethbridge 2016, Olds, Scott	Lethbridge 2015, Vermilion, St. Albert
Contrast	***P* value**	***P* value**
NTC vs. Glypho 450	0.0008*	0.0008*
NTC vs. Glypho 900	0.0008*	0.0008*
Glypho 450 vs. Glypho 900	0.0008*	0.0008*
Glypho @ 450, 900 vs. Glypho @ 450, 900 + Propoxy 10	0.3072	0.0056*
Glypho @ 450, 900 vs. Glypho @ 450, 900 + Pyrox	1.0000	0.0784
Glypho @ 450, 900 + Propoxy 10 vs. Glypho @ 450, 900 + Propoxy 7.5	1.0000	1.0000
Glypho @ 450, 900 + Propoxy 10 vs. Glypho @ 450, 900 + Flucarb/triben	1.0000	1.0000
Glypho @ 450, 900 + Propoxy 10 vs. Glypho @ 450, 900 + Pyrox	0.2984	1.0000

Figure 3-1 Trial 1 estimates of visual herbicide control of ALS and VLCFA short residual herbicides applied PRE in combination with varying rates of glyphosate at 6 sites. Visual estimates of herbicide control (0-100%) were made 28 DAT. Pre-planned non-orthogonal contrasts were used to analyze combinations of residual herbicides and glyphosate, and adjusted using a Bonferroni correction factor. Error bars indicate standard error of the mean.



Contrast	***P* value**
NTC vs. Glypho 450	1.0000
NTC vs. Glypho 900	1.0000
Glypho 450 vs. Glypho 900	1.0000
Glypho @ 450, 900 vs. Glypho @ 450, 900 + Propoxy 10	1.0000
Glypho @ 450, 900 vs. Glypho @ 450, 900 + Pyrox	0.0088*
Glypho @ 450, 900 + Propoxy 10 vs. Glypho @ 450, 900 + Propoxy 7.5	1.0000
Glypho @ 450, 900 + Propoxy 10 vs. Glypho @ 450, 900 + Flucarb/triben	1.0000
Glypho @ 450, 900 + Propoxy 10 vs. Glypho @ 450, 900 + Pyrox	0.3064

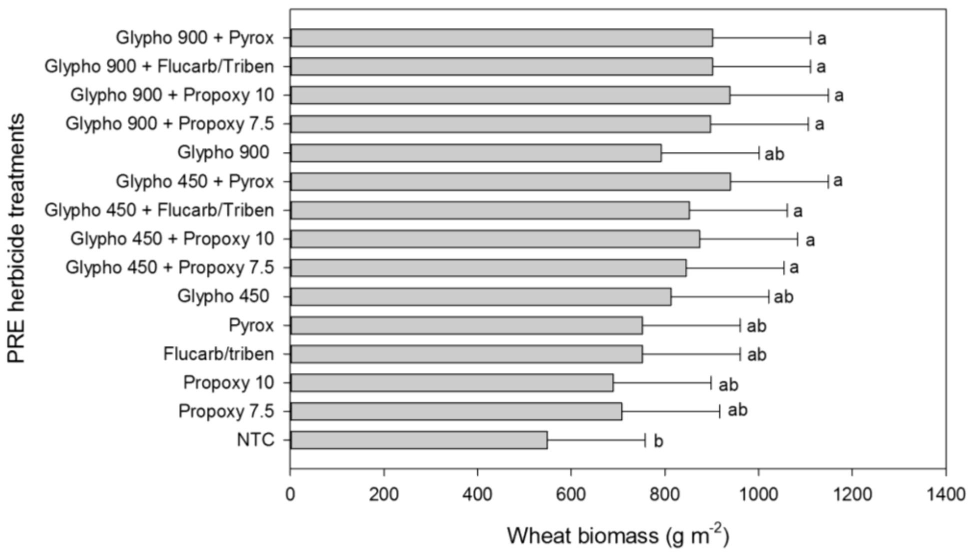
Figure 3-2 Trial 1 evaluation of ALS and VLCFA short residual herbicides efficacy applied PRE in combination with varying rates of glyphosate at 6 sites on foxtail barley seedlings. Density of seedlings (seedlings m^{-2}) was recorded 28 DAT. Pre-planned non-orthogonal contrasts were used to analyze combinations of residual herbicides and glyphosate, and adjusted using a Bonferroni correction factor. Error bars indicate standard error of the mean.



Contrast	***P* value**
NTC vs. Glypho 450	0.0008*
NTC vs. Glypho 900	0.0008*
Glypho 450 vs. Glypho 900	1.0000
Glypho @ 450, 900 vs. Glypho @ 450, 900 + Propoxy 10	1.0000
Glypho @ 450, 900 vs. Glypho @ 450, 900 + Pyrox	1.0000
Glypho @ 450, 900 + Propoxy 10 vs. Glypho @ 450, 900 + Propoxy 7.5	1.0000
Glypho @ 450, 900 + Propoxy 10 vs. Glypho @ 450, 900 + Flucarb/triben	1.0000
Glypho @ 450, 900 + Propoxy 10 vs. Glypho @ 450, 900 + Pyrox	1.0000

Figure 3-3 Trial 1 evaluation of ALS and VLCFA short residual herbicides efficacy applied PRE in combination with varying rates of glyphosate at 6 sites on foxtail barley biomass. Twenty-one days prior to harvest, foxtail barley (shoots and seedlings) was cut at the

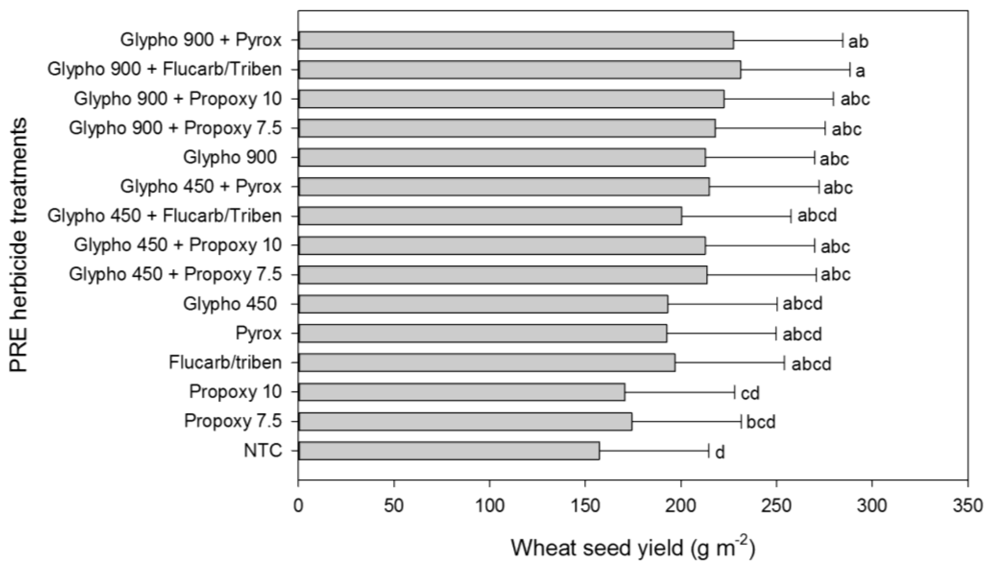
soil surface from one 0.25 m^2 quadrat per plot. Plant biomass was dried at 50 °C to a constant moisture for 5 to 7 days and weighed to determine shoot dry mass. Pre-planned non-orthogonal contrasts were used to analyze combinations of residual herbicides and glyphosate, and adjusted using a Bonferroni correction factor. Error bars indicate standard error of the mean.



Contrast	***P* value**
NTC vs. Glypho 450	0.0080*
NTC vs. Glypho 900	0.0200*
Glypho 450 vs. Glypho 900	1.0000
Glypho @ 450, 900 vs. Glypho @ 450, 900 + Propoxy 10	0.5576
Glypho @ 450, 900 vs. Glypho @ 450, 900 + Pyrox	0.3184
Glypho @ 450, 900 + Propoxy 10 vs. Glypho @ 450, 900 + Propoxy 7.5	1.0000
Glypho @ 450, 900 + Propoxy 10 vs. Glypho @ 450, 900 + Flucarb/triben	1.0000
Glypho @ 450, 900 + Propoxy 10 vs. Glypho @ 450, 900 + Pyrox	1.0000

Figure 3-4 Trial 1 evaluation of ALS and VLCFA short residual herbicides applied PRE in combination with varying rates of

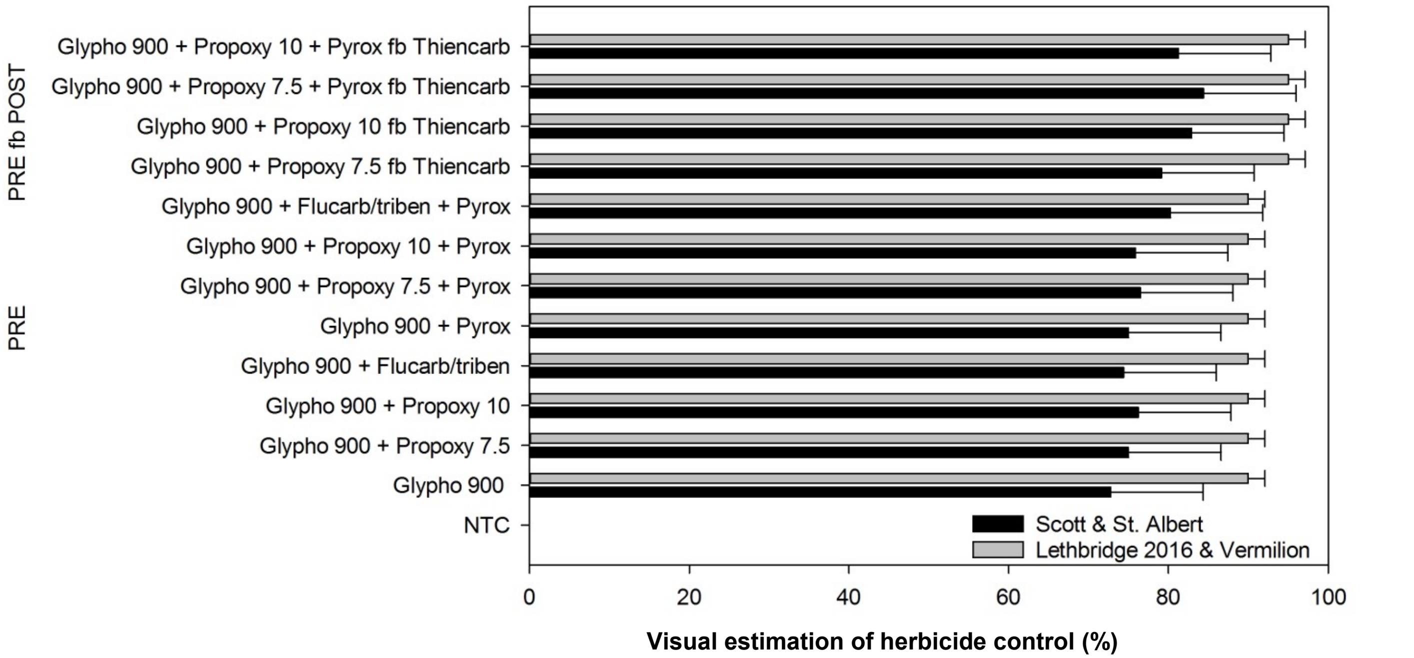
glyphosate at 6 sites affect on wheat biomass. Twenty-one days prior to harvest, wheat shoots were cut at the soil surface from one 0.25 m^2 quadrat per plot. Plant biomass was dried at 50 °C to a constant moisture for 5 to 7 days and weighed to determine shoot dry mass. Pre-planned non-orthogonal contrasts were used to analyze combinations of residual herbicides and glyphosate, and adjusted using a Bonferroni correction factor. Error bars indicate standard error of the mean.



Contrast	***P* value**
NTC vs. Glypho 450	0.2160
NTC vs. Glypho 900	0.0048*
Glypho 450 vs. Glypho 900	1.0000
Glypho @ 450, 900 vs. Glypho @ 450, 900 + Propoxy 10	1.0000
Glypho @ 450, 900 vs. Glypho @ 450, 900 + Pyrox	0.9376
Glypho @ 450, 900 + Propoxy 10 vs. Glypho @ 450, 900 + Propoxy 7.5	1.0000
Glypho @ 450, 900 + Propoxy 10 vs. Glypho @ 450, 900 + Flucarb/triben	1.0000
Glypho @ 450, 900 + Propoxy 10 vs. Glypho @ 450, 900 + Pyrox	1.0000

Figure 3-5 Trial 1 evaluation of ALS and VLCFA short residual herbicides applied PRE in combination with varying rates of glyphosate at 6 sites affect on wheat seed yield. Plots were harvested when the crop reached grain moisture content <14%, a stage of

BBCH 89, to determine crop seed yield. Wintersteiger plot-harvesting combines were used at each location, harvest width being 1.8 m, for the entire length of the plot. Crop seed samples were cleaned and weighed. Pre-planned non-orthogonal contrasts were used to analyze combinations of residual herbicides and glyphosate, and adjusted using a Bonferroni correction factor. Error bars indicate standard error of the mean.



	Scott & St. Albert	Lethbridge 2016 & Vermilion	Lethbridge 2015 & Olds
Contrast	***P* value**	***P* value**	***P* value**
Glypho 900 vs. Glypho 900 + Propoxy 10	0.7264	1.0000	1.0000
Glypho 900 vs. Glypho 900 + Propoxy 10 + Pyrox	0.9300	1.0000	1.0000
Glypho 900 vs. Glypho 900 + Propoxy 10 fb Thiencarb	0.0008*	0.0008*	1.0000
Glypho 900 vs. Glypho 900 + Propoxy 10 + Pyrox fb Thiencarb	0.0064*	0.0008*	1.0000

Figure 3-6 Trial 2 visual estimates of herbicide control of ALS and VLCFA short residual herbicides applied PRE and POST in combination with a standard of glyphosate at 6 sites. Visual estimates of herbicide control (0-100%) were made 28 DAT. Pre-planned non-orthogonal contrasts were used to analyze combinations of residual herbicides and glyphosate, and adjusted using a Bonferroni correction factor. Error bars indicate standard error of the mean.

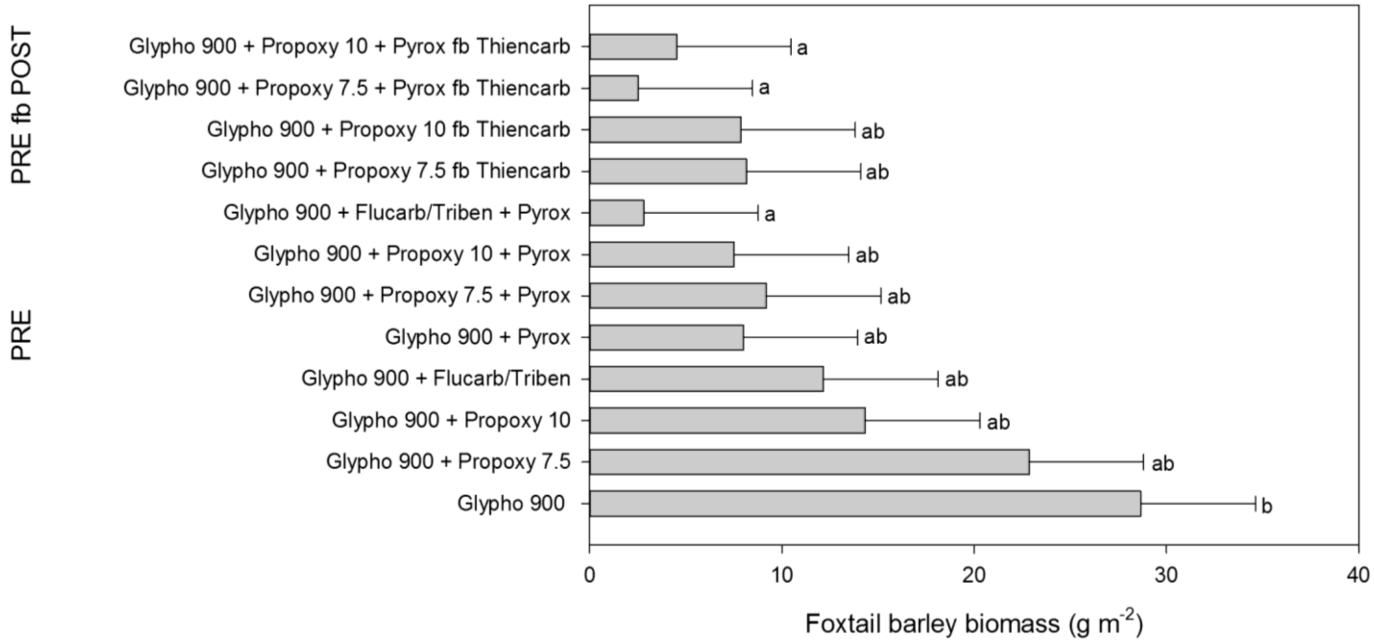


Figure 3-7 Trial 2 evaluation of ALS and VLCFA short residual herbicides efficacy applied PRE and POST in combination with a standard rate glyphosate at 6 sites on foxtail barley biomass. Twenty-one days prior to harvest, foxtail barley (shoots and seedlings) was cut at the soil surface from one 0.25 m^2 quadrat per plot. Plant biomass was dried at 50 C to a constant moisture for 5 to 7 days and weighed to determine shoot dry mass. When herbicide treatment was found to be significant ($P \leq 0.05$), means were separated using Tukey method. Error bars indicate standard error of the mean.

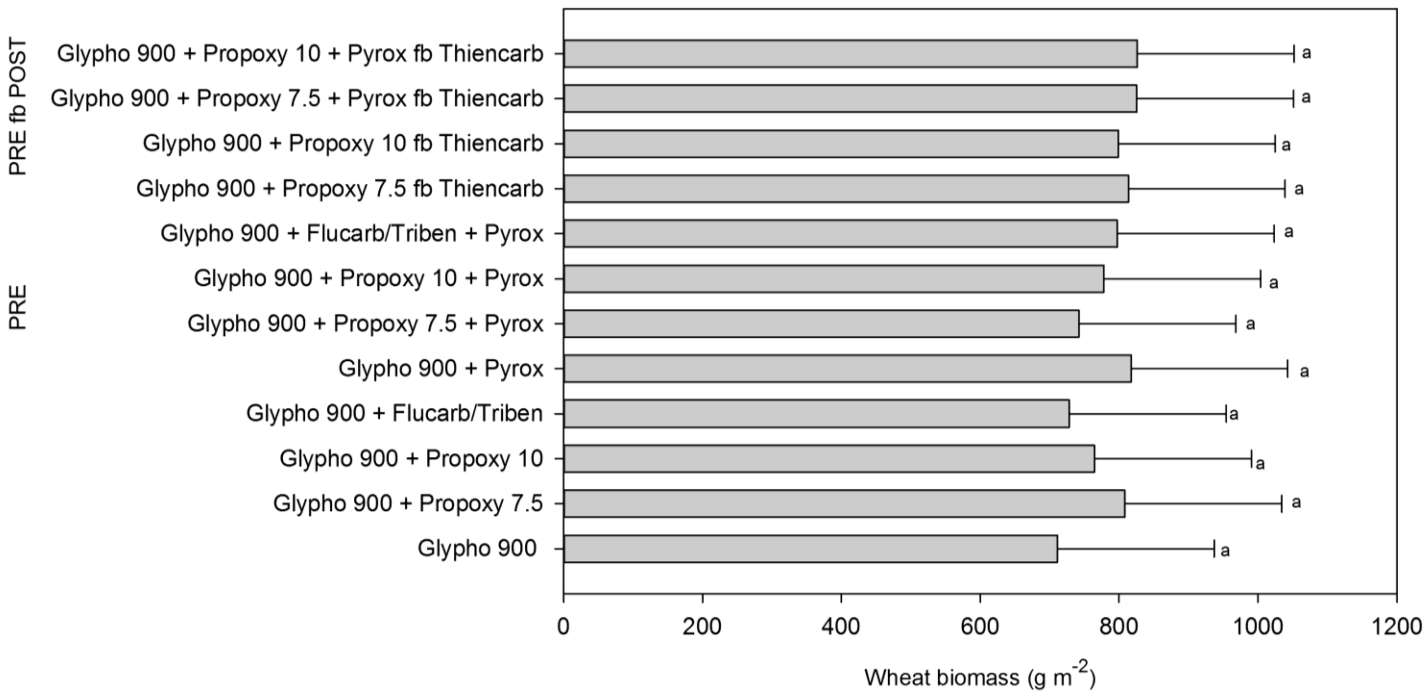


Figure 3-8 Trial 2 evaluation of ALS and VLCFA short residual herbicides applied PRE and POST in combination with a standard rate glyphosate at 6 sites affect on wheat biomass. Twenty-one days prior to harvest, wheat shoots were cut at the soil surface from one 0.25 m^2 quadrat per plot. Plant biomass was dried at 50 C to a constant moisture for 5 to 7 days and weighed to determine shoot dry mass. When herbicide treatment was found to be significant ($P \leq 0.05$), means were separated using Tukey method. Error bars

indicate standard error of the mean.

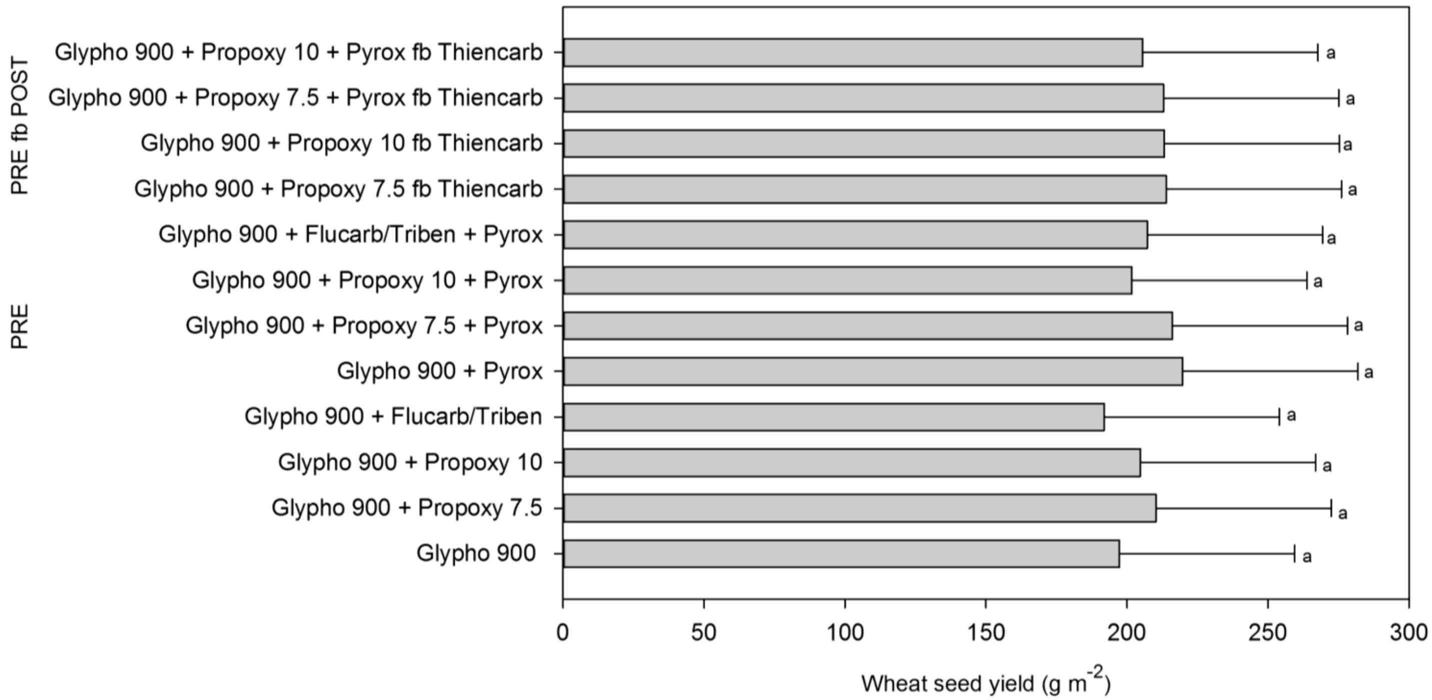


Figure 3-9 Trial 2 evaluation of ALS and VLCFA short residual herbicides applied PRE and POST in combination with a standard rate glyphosate at 6 sites affect on wheat seed yield. Plots were harvested when the crop reached grain moisture content <14%, a stage of BBCH 89, to determine crop seed yield. Wintersteiger plot-harvesting combines were used at each location, harvest width being 1.8 m, for the entire length of the plot. Crop seed samples were cleaned and weighed. When herbicide treatment was found to be

significant ($P \leq 0.05$), means were separated using Tukey method. Error bars indicate standard error of the mean.

Chapter Four: Seedling recruitment of foxtail barley (*Hordeum jubatum*) in western Canadian spring wheat

4.1. Introduction

Foxtail barley (*Hordeum jubatum*) is a native perennial bunch grass species that has increased in abundance and density in western Canada as a result of the adoption of conservation tillage systems (Best et al. 1978; Leeson et al. 2005). Foxtail barley establishes in rangeland, ruderal areas and cropland (Best et al. 1978). Foxtail barley has two primary cohorts of seedling recruitment (Badger and Ungar 1989). The first period is in early August when seed is shed from the mature plants. The second begins in April and continues throughout the season, however, the peak of the spring seedling recruitment occurs between April and May (Badger and Ungar 1989; Chepil 1946). Seedlings that are recruited in the spring are seeds that have remained viable over the winter period. Badger and Ungar (1989) suggest that the two peaks of germination for foxtail barley are a result of the availability of safe sites for germination in the fall and spring, rather than caused by seed dormancy. Foxtail barley has no primary seed dormancy but secondary dormancy can be induced. Baskin and Baskin (1988) reported that it is uncommon for polycarpic herbaceous species, such as foxtail barley, to have a fall germination period as only 14 of 122 species monitored in their study followed this lifecycle. A study conducted by Badger and Ungar (1994) working in saline marshes found that the size of the foxtail barley seed bank populations varied dramatically from one year to the next depending on changes in environmental conditions. Moreover, changes in the seed bank throughout the growing season occur as new seedlings are recruited throughout the growing season (Badger and Ungar 1989). They reported that the seed bank had 3,260 seeds m^{-2} in February and was reduced to 470 seeds m^{-2} by May. Badger and Ungar (1991, 1994) reported that the seed bank could have as many as 4,715 foxtail barley seeds m^{-2} before winter in a dense population of foxtail barley. Thompson and Grime (1979) state that because foxtail barley exhibits fall and spring germination periods, it indicates that the species may have a Type III persistent seed bank. Type III seed banks generally have some seeds that germinate soon after release and others which are more persistent in the soil. The continuance of a small persistent seed bank and seedling population from the spring and fall germination periods serves to maintain populations of foxtail barley in habitats that fluctuate with salinity and moisture levels, and where salt stress may increase beyond the tolerance limits of seeds (Badger and Ungar, 1994; Ungar 2001).

Halophytic communities or roadside populations adjacent to arable farmland influence the weed communities in the margins of fields. These halophytic communities are a seed source that can be distributed into agricultural land and lead to the increased abundance of a given weed species (Hume and Archibold 1986). A field study conducted in Saskatchewan by Hume and Archibold (1986) reported that seed rain from grass seed with no wind dispersal from a pasture adjacent to a cultivated field significantly impacted the seed reservoir in the cultivated field. However, the reservoir (seed bank) was only influenced a few meters into the field. Blumenthal and Jordan (2001) concluded that although the off-site seed reservoir influenced the weed dynamics in the margin of a cultivated field, there was little value of controlling the perennial weeds in this area. Frequent cultivation in the cropping system prevented the establishment of these species further into the cultivated areas (Hume and Archibold 1986; Blumenthal and Jordan 2001). However, over the past three decades, conservation tillage systems have been widely adopted in the Canadian prairies, therefore a reliance on chemical weed control has been increased.

Soil moisture concentrations and fluctuations influence foxtail barley seed germination. Boyd and Van Acker (2003) found that foxtail barley had significantly greater emergence when moisture concentrations fluctuated between field capacity and 1/3rd field capacity compared to fluctuating between field capacity and 1/6th field capacity. This may help explain why foxtail barley is more commonly found in wet fertile soils (Best et al. 1978).

Temperature also influences foxtail barley seedling germination. Ungar (1982) found that the high germination percentages of halophytes in the spring were attributed to reductions in soil salinity and to diurnal fluctuations in temperature. In relation to the fall germination period of foxtail barley, Badger and Ungar (1989) reported that temperature is the predominant environmental factor that delays the germination of foxtail barley. Warm summer temperatures delay the germination of the seeds, but cooler fluctuating temperatures of the fall break the temporary dormancy of the seed and germination begins (Badger and Ungar 1989).

The objective of this study was to monitor foxtail barley seedling recruitment in agricultural land to better understand the timing and percentage of seedling recruitment that occurs at each of the spring and fall cohort periods in western Canada. Because efficacy and the length of the residual control varies with herbicides, some herbicides may be more useful than others. Using the data generated from this research, a theoretical estimate of spring recruited foxtail barley seedling control with PRE residual herbicide was developed. Assumptions made about application timing, cumulated GDDs, and length of residual activity were used to build a model that can estimate the effectiveness of a PRE residual herbicide application on foxtail barley seedlings. Information may allow agronomists to optimize herbicide regimes, possibly including the use of pre-seeding short residual herbicides to control foxtail barley in spring wheat.

4.2. Materials and Methods

4.2.1. Field Experiments

Field studies were conducted at 6 sites over two years (Table 4-1) at Lethbridge, Olds and Scott, SK in 2015 and Lethbridge, Vermilion and St. Albert, AB in 2016. Trials were established on no-till agricultural crop-land naturally infested with moderate to dense populations of foxtail barley (Table 4-1). Scott had uniform populations while the remaining sites had higher densities closer to the seed source (headland areas), therefore, replicates were placed parallel to population densities, maintaining a uniform population in each replicate as possible. Previous years stubble type varied by site. A pre-seeding application of florasulam at 4.94 g ai ha^{-1} was applied at Lethbridge 2015-2016, Scott and St. Albert to remove potentially confounding broadleaf weed species. No other herbicides were applied to plots throughout the remainder of the growing season. Plots were seeded and fertilized to simulate a spring wheat crop, and to evaluate its effect on foxtail barley seedling recruitment. AC Harvest hard red spring wheat was sown at a depth of 3 cm and a rate of 350 seeds m^{-2} between the dates of April 29th to May 22nd at all sites using a no-till Fabro plot seeder with Atom jet openers spaced at 20 cm. Each site was fertilized with urea, monoammonium phosphate and ammonium sulfate as per soil test recommendations to achieve a wheat seed yield of 2700 kg ha^{-1}. Sowing of the sites occurred at typical timings for each area (Table 4-2). Precipitation during the growing season varied by site (Table 4-3).

4.2.2. Experimental Design

This experiment was incorporated into a herbicide evaluation study by utilizing the non-treated check (NTC) plots as a representation of the existing natural populations of foxtail barley that were present at each site. This experiment was arranged in a randomized complete block design with four replicates. Plots were 2 m wide and 7.5 m long at all sites except Scott where they were 5.5 m long.

4.2.3. Data Collection

Mature foxtail barley plants were initially quantified at each site using 20, 0.25 m^{-2} quadrat counts. Foxtail barley seedling recruitment was monitored weekly at each site from planting date until October 31st. To quantify seedling emergence, two 0.25 m^2 subplots were established in the front and back of each NTC plot of each replicate. Newly emerging foxtail barley seedlings were marked weekly with avian leg bands and counted once per week to evaluate cumulative foxtail barley seedling recruitment throughout the growing season. Cumulative growing degree days (GDD, base 5°C) were calculated beginning on January 1st of 2015 and 2016. Fifteen soil samples were randomly collected from the test area then bulked for analysis to determine soil texture, OM, pH and EC.

4.2.4. Statistical Analyses

Cumulative spring foxtail barley seedling recruitment at each site based on cumulative GDD was fitted to a three-parameter Gompertz model using JMP 13.0.0 software (SAS Institute 2010, SAS Campus Drive, Cary, NC 27513, SAS Institute, Inc.). The model fitted was

$$E\ (\%) = a * \exp\{-\exp[-b * (GDD - c)]\}$$

where E (%) is the total seedling recruitment (%) at cumulated GDD value, a is the asymptote, b is rate of seedling recruitment, and c is the inflection point.

The same model was used to fit cumulative spring foxtail barley seedling recruitment at each site based on time. The fitted model was

$$E\ (\%) = a * \exp\{-\exp[-b * (DATE - c)]\}$$

where E (%) is the total seedling recruitment (%) at cumulated time, a is the asymptote, b is rate of seedling recruitment, and c is the inflection point.

Cumulative fall foxtail barley seedling recruitment at each site based on cumulative GGD was fitted to a three-parameter logistic model using JMP (version 13.0). The model fitted was

$$E\ (\%) = \frac{a}{\{1 + \exp[-b * (GDD - c)]\}}$$

where E (%) is the total seedling recruitment (%) at cumulated GDD value, a is the asymptote, b is rate of seedling recruitment, and c is the inflection point.

The same model was used to fit cumulative fall foxtail barley seedling recruitment at each site based on time. The fitted model was

$$E\ (\%) = \frac{a}{\{1 + \exp[-b * (DATE - c)]\}}$$

where E (%) is the total seedling recruitment (%) at cumulated time, a is the asymptote, b is rate of seedling recruitment, and c is the inflection point. All coefficient values for spring and fall seedling recruitment x GDD regressions can be found in Table 4-5 and Table 4-7. Coefficient values not presented for DATE regressions.

4.3. Results and Discussion

4.3.1. Growing Season Weather

Annual observed precipitation varied among sites. Lethbridge 2015 received 58% of the growing season rainfall long-term average (GSR LTA (Table 4-1)). Scott and Lethbridge 2016 received 82% and 84% of the GSR LTA. Olds, Vermillion and St. Albert received normal precipitation for the growing season. Differences in cumulated rainfall between sites is a key factor that influences foxtail barley population growth and vigor throughout the growing season. Blackshaw et al. 1998, 1999 also found a similar trend in their studies. Average temperatures were recorded at each site for the growing season (data not shown). Sowing of trials was completed at typical timings appropriate for the location (Table 4-2). Trials were located on non-saline sites, therefore we do not anticipate that EC influenced crop seed yield.

Two major cohorts of seedling emergence were observed at all six sites. The first cohort of seedling recruitment occurred in the spring. Initiation of seedling recruitment varied by site, however, the timeframe of spring recruitment was primarily restricted to early till late May. Spring seedling recruitment extended into late July, however recruitment began to slow around early June. Initiation of fall seedling recruitment generally began late-August to early September, which was a result of the release of newly produced seed from mature plants. Newly produced foxtail barley seed has little dormancy, therefore if proper conditions for germination are available, seeds begin to germinate immediately after dispersal. Fall seedling recruitment generally ceased in late-September and early October, however, recruitment continued into late October at sites located in more southern latitudes (Figure 4-1). To best model the seedling recruitment cohorts, the spring and fall cohorts were modelled separately to more closely evaluate the relationship between recruitment, cumulated GDDs and time. Total cumulative seedling recruitment varied by site (Table 4-1). A maximum of 703 cumulative foxtail barley seedlings m^{-2} emerged throughout the growing season at Olds, whereas a minimum of 71 seedlings m^{-2} emerged at Vermilion. Examining seedling recruitment in relation to GDDs and time is necessary to develop effective recommendations for PRE herbicide application to control foxtail barley seedlings. Furthermore, examining seedling recruitment in relation to time helps evaluate how seedling recruitment coincides with typical field operations such as PRE herbicide timing and sowing.

4.3.2. Spring cohort seedling recruitment

A 3P sigmoid curve was used to best describe the shape of spring seedling recruitment. The “S” shape of this model has two inflection points, one indicating the initiation of seedling recruitment in the spring, the other indicates when seedling recruitment approaches completion. The slope of this regression indicates the rate of which seedling recruitment occurs. Spring foxtail barley seedling recruitment varied among sites (Figure 4-2). At Olds and Scott, seedling recruitment began at 78.4 and 80.6 cumulated GDD, respectively, while seedling emergence at the remaining sites began between 161 and 264 cumulated GDD. Our models show that rate (slope) of seedling recruitment varied across sites (Table 4-5). Unique interactions of soil moisture, GDD and density of foxtail barley seeds in the soil seed bank likely cause rate of seedling recruitment to vary. Therefore, because rate of seedling recruitment is found to vary by site, this potentially can cause recommendations for herbicide application to be ineffective if a high proportion of recruitment occurs outside of a proposed control timing window. Cumulative emergence at 30, 50 and 80% found in Table 4-4 show that foxtail barley seedling recruitment varies among sites, which again can cause potential failures in control if large proportions of recruitment occur outside of a control window. In general, all sites shared a common pattern of seedling emergence, only the initiation of seedling recruitment varied to some degree, except for in the case of Olds. Olds seedling recruitment varied considerably from the other sites. This likely occurred as the total number of seedling recruitment per m^{-2} was considerably higher when compared to the other sites.

Foxtail barley seedling recruitment based on accumulated time varied slightly from that of accumulated GDD. As expected, more southern sites began seedling recruitment earlier (Figure 4-3). Lethbridge 2015-2016, Olds and Scott seedling recruitment began early- to mid-May, whereas at St. Albert and Vermilion recruitment began late-May. Although seedling recruitment began at different times throughout May, recruitment ceased mid-June for Lethbridge 2016, Scott, St. Albert and Vermilion, and early-June at Lethbridge 2015 and mid-July at Olds. The differences in length of seedling recruitment period between the sites is likely caused by soil moisture/temperature interactions, density of seed in the seed bank, and availability of safe-sites. Sites at more northern latitudes (St. Albert and Vermilion) exhibited a shorter period of seedling recruitment, suggesting that there is intraspecific variation among foxtail barley populations adapted to length of the growing season. The results of Badger and Ungar 1994 are similar to that of this study. Badger and Ungar 1994 found that the peak period of foxtail seedling recruitment occurred May, however, their results suggest that peak recruitment carries into July, whereas the results from this study suggest that peak emergence tapers off in June. The differences in peak recruitment may be a result of the test locations. Badger and Ungar 1994 conducted their study on a lake bed, which had an extremely high amount of foxtail barley seedling present, whereas the test areas in these experiments were conducted in cropland, which had substantially lower amounts of foxtail barley seed in the seed bank.

4.3.3. Theoretical foxtail barley spring seedling control

A standard application of glyphosate PRE on the suggested dates in Table 4-2 would have very little to no effect on controlling newly emerging spring foxtail barley seedlings as they are typically not emerged at this time (0-4% of total spring seedling population emerged). Therefore, by tank-mixing a short residual ALS or VLCFA herbicide we hypothesize to achieve some residual control of later emerging seedlings if the herbicides were applied at these same timings.

Theoretical control of foxtail barley spring recruited seedlings is based on the PRE short residual herbicide application dates given in Chapter three (Table 4-2). An assumption is made that the short residual herbicides used in Chapter 3 have efficacy on emerging foxtail barley seedlings for a period of 28 days. Therefore, the accumulated growing degree days were calculated for 28 days following the PRE herbicide application, and an assumption was made that the herbicides could achieve 100% control of the seedlings that emerged in the 28 day time period. With these assumptions, estimated effective control values (%) of the cumulative spring seedling recruitment population were made using the spring cohort seedling recruitment regressions (Figure 4-4). The lowest estimated control was achieved at Lethbridge 2016 with an estimation of 14.9% of the newly recruited seedlings being controlled 28 days after treatment (DAT). Olds and Lethbridge 2015 had slightly increased control at estimations of 28.7% and 40.7%, respectively. Estimated control at St. Albert and Vermilion was 82.2% and 83.3% respectively, with the highest level of control occurring at Scott, which estimated control at 88.5%. From these results, we can conclude that the percentage of seedlings recruited within the control window varies greatly by site. Therefore, the use of a short residual herbicide applied with glyphosate will result in varying levels of control, specifically, a low percentage of seedling control is likely to occur at sites located in southern latitudes.

From the model, an observation can be made that greater control of emerging seedlings can be achieved when a residual herbicide is applied when a greater amount of GDDs have accumulated. In Lethbridge 2015 and 2016, PRE herbicides were applied earlier in the growing season when less GDDs had accumulated. Field operations were initiated because soil temperatures were warm enough for producers to begin sowing. In contrast, sites such as St. Albert and Vermilion required more accumulated GDDs in order to begin sowing. This difference in accumulated GDDs and sowing date between the sites located at different latitudes suggests that when PRE herbicides are used at sites located in more northern latitudes, they will more effectively target a larger percentage of the total spring recruited seedling population.

However, the assumptions made in this model may not be valid in real-world conditions. For example, it is unlikely that the PRE residual herbicides suggested in this study will achieve 100% control of foxtail barley seedling recruitment for a total of 28 DAT. Furthermore, PRE soil applied herbicide efficacy is influenced by soil OM and environmental conditions in some situations. Tidemann et al. (2014) and Mangin et al. (2017) found that pyroxasulfone efficacy on wild oat was reduced when soil organic matter increased. Therefore, the theoretical control percentages suggested using this model may need to be reduced by 10-30% to achieve a more realistic control estimation. For example, the 88.5% estimated control of spring emerged seedlings at Scott would not likely occur. A more accurate estimation would be 55.5-75.5% control of the total spring recruited seedling population. Moreover, delaying PRE herbicide application and planting to better target foxtail barley emergence is not consistent with other weed management and agronomic practices such as early seeding to encourage strong crop competition against weeds early in the growing season (O'Donovan et al. 2007). Therefore, PRE short residual herbicides applied alone or in combination with glyphosate would likely not provide complete control of spring emerging foxtail barley seedlings. In the best case, an estimated 25-45% of the spring recruited seedling cohort would remain even after the application of a PRE short residual herbicide in combination with glyphosate. Therefore, a POST application would likely be required to target spring emerged seedlings that escape control from PRE herbicides. However, the use of a PRE short residual herbicide in combination with glyphosate should be recommended to help manage the spring recruited seedling cohort.

4.3.4. Fall cohort seedling recruitment

Similar to that of spring seedling recruitment, fall seedling recruitment varied among sites (Table 4-6; Figure 4-5). At Olds and Scott, the fall seedling recruitment period began after 320 cumulated GGD (1220 cumulated GDD over growing season). Lethbridge 2016 began fall seedling recruitment at a similar period compared to Olds and Scott, however, the emergence rate of seedlings at Lethbridge 2016 was slower compared to the other two sites. St. Albert and Vermilion began fall seedling recruitment at 420 (1320 total) cumulated growing degree days; an emergence rate similar to that of Olds and Scott. And finally, Lethbridge 2015 began fall seedling recruitment after 740 (1640 total) cumulated GDDs. Its seedling emergence rate (slope) differed from that of the other sites. Lethbridge 2015 had a more gradual increase in seedling emergence compared to that of Olds, Scott, St. Albert and Vermilion (Table 4-5). Similar to the results found with the spring seedling cohort, the fall seedling cohort completed its cycle in relation to when it began. For example, Olds and Scott began their seedling recruitment period earliest out of all the sites; they correspondingly completed recruitment with fewer accumulated GDD. Moreover, these results are in agreement with the spring seedling recruitment results, suggesting that genetically isolated populations of foxtail barley show intraspecific variation compared to populations found at other latitudes. Populations found at higher latitudes tend to complete their seedling recruitment period with lower cumulated GDDs as a result of adaptation to a shorter growing season. Furthermore, the slope of the four more northern sites (Scott, Olds, Vermilion, St. Albert) provide additional explanation that northern latitude sites also have a shorter seedling recruitment period compared to more southern latitude sites such as Lethbridge 2015 and 2016 (Table 4-7). This trend can also be observed in Figure 4-6.

As with spring seedling recruitment, the differences in length of seedling recruitment among the sites is likely caused by soil moisture/temperature interactions, density of seed in the seed bank, and distribution of safe-sites. We hypothesize that fall seedling recruitment is inherently more variable than the spring seedling recruitment period as it is more strongly influenced by environmental conditions at the time of seed dispersal. Multiple studies have shown that foxtail barley seedling recruitment is strongly influenced by soil moisture/ temperature and salinity interactions (Boyd and Van Acker 2003; Ungar 1982; Badger and Ungar 1989).

4.4. Conclusion

Two cohorts of seedling emergence were observed at all six sites. The first cohort of seedling recruitment occurred in the spring. Initiation of seedling recruitment varied by site, however the timeframe of spring recruitment was primarily restricted to early until late May. Spring seedling recruitment extended into late July, however, recruitment began to slow around early June. The findings of this study suggest that the spring seedling cohort can extend into mid-summer depending on environmental conditions, which differs from the results of Badger and Ungar (1989) and Chepil (1946). Spring foxtail barley seedling recruitment varied among sites. At Olds and Scott, seedling recruitment began at 78.4 and 80.6 cumulated GDD, respectively, while seedling emergence at the remaining sites began between 161 and 264 cumulated GDD. Unique interactions of soil moisture, GDD and density of foxtail barley seeds in the soil seed bank likely cause rate of seedling recruitment to vary. Therefore, because rate of seedling recruitment is found to vary by site, this potentially can cause recommendations for herbicide application to be ineffective if a high proportion of recruitment occurs outside of a proposed control timing window. In general, all sites shared a common pattern of seedling emergence, only the initiation of seedling recruitment varied to some degree, except for Olds. Olds seedling recruitment varied considerably from the other sites. This likely occurred as the total number of seedling recruitment per m^{-2} was considerably higher when compared to the other sites.

Initiation of fall seedling recruitment generally began late-August to early September, which results from the release of newly produced seed from the mature plants. Fall seedling recruitment generally ceased late-September, early October in northerly sites, but continued into late October at sites located in more southern latitudes. The results from the fall seedling recruitment regressions are in agreement with the spring seedling recruitment results, suggesting that genetically isolated populations of foxtail barley show intraspecific variation compared to populations found at other latitudes. Populations found at higher latitudes tend to complete their seedling recruitment period with lower cumulated GDDs as a result of having a shorter growing season.

A standard PRE application of glyphosate at a typical spring timing would have very little to no effect on controlling newly emerging spring foxtail barley seedlings as they are typically not emerged at this time (0-4% of total spring seedling population emerged).

When incorporating a PRE residual herbicide to glyphosate, the lowest estimated control was achieved at Lethbridge 2016 with 14.9% of the newly recruited seedlings being control following 28 days after treatment (DAT). Olds and Lethbridge 2015 had slightly increased control at estimations of 28.7% and 40.7%, respectively. Estimated control at St. Albert and Vermilion was 82.2% and 83.3% respectively, with the highest level of control occurring at Scott, which estimated control at 88.5%. From these results we can conclude that the percentage of seedlings recruited within the control window varies greatly by site. Therefore, the use of a short residual herbicide applied with glyphosate will result in varying levels of control, specifically, a low percentage of seedling control is likely to occur at sites located in southern latitudes.

From the model, an observation can be made that greater control of emerging seedlings can be achieved when a residual herbicide is applied when a greater amount of GDDs have accumulated. The difference in accumulated GDDs and sowing date between the sites located at different latitudes suggests that when PRE herbicides are used at sites located in more northern latitudes, they will more effectively target a larger percentage of the total spring recruited seedling population.

The assumptions made in this model may not uphold in real-world conditions. Therefore, the theoretical control percentages suggested using this model may need to be reduced to achieve a more realistic control estimation. Moreover, delaying PRE herbicide application, and planting to better target foxtail barley seedling emergence does not follow other weed management and agronomic practices such as early seeding to encourage strong crop competition against weeds early in the growing season (O'Donovan et al. 2007). Therefore, PRE short residual herbicides applied alone or in combination with glyphosate would likely not provide complete control of spring emerging foxtail barley seedlings. In the best case, an estimated 25-45% of the spring recruited seedling cohort would remain after the application of a PRE short residual herbicide in combination with glyphosate. Therefore, a POST application will likely be required to target spring emerged seedlings that escape control after a PRE herbicide application. However, the use of a PRE short residual herbicide in combination with glyphosate should be recommended to help manage the spring recruited seedling cohort.

Table 4-1 Plant population and soil characteristics for each location including soil type, percent composition of sand, silt, clay, and organic matter (OM)[a], soil pH[b] as well as soil EC.

Year	Location	Mature (m^{-2})	SE	Total cumulative seedling recruitment (m^{-2})	SE	Soil texture	Sand	Silt	Clay	OM	Soil pH	EC (mS/cm)
							--------------%-----------					
2015	Lethbridge	44	6.6	204	1.5	Sandy clay loam	54.1	18.7	27.2	2.7	7.8	0.3
	Olds	28	2.8	703	4.8	Loam	35.8	40.2	24.0	8.0	6.0	0.5
	Scott	76	3.8	182	0.7	Loam	36.4	47.4	16.2	2.8	5.8	0.1
2016	Lethbridge	33	5.0	306	1.3	Sandy clay loam	65.8	12.2	22.0	2.9	7.9	0.5
	Vermilion	17	2.6	71	2.4	Sandy loam	68.6	20.7	10.7	5.5	7.2	0.34
	St. Albert	24	2.4	392	4.1	Silty clay	14.0	43.1	42.9	11.5	6.5	0.85

[a] Abbreviations: OM, organic material; EC, electrical conductivity.

[b] Soil characteristics taken at 0-15 cm depth.

[c] Lethbridge 2016 different field location than 2015.

Table 4-2 Dates of wheat planting and PRE application.[a]

Year	Location	PRE application	Planting date
2015	Lethbridge	April 27	May 4
	Olds	May 5	May 12
	Scott	May 15	May 22
2016	Lethbridge	April 22	April 29
	Vermilion	May 10	May 17
	St. Albert	May 12	May 19

[a] Abbreviations: PRE, pre-emergence

Table 4-3 Summary of precipitation during growing season and PRE application, and soil moisture at PRE application.[a]

		Precipitation						
Year	Location	GSR	GSR LTA	% of GSR LTA	APPR[b]	APPR LTA	% of APPR LTA	Soil moisture[c]
		------mm------		--------%-------	--------mm----------		--------%--------	Vol. (%)
2015	Lethbridge	172	298	58	2	31	6	22.0
	Olds	395	386	102	26	35	74	29.2
	Scott	240	291	82	4	32	13	15.7
2016	Lethbridge	249	298	84	13	30	43	18.3
	Vermilion	363	325	112	22	29	76	9.7
	St. Albert	375	349	107	77	29	266	20.1

[a] Abbreviations: PRE, pre-emergence; GSR, growing season (April-October) rainfall; LTA, long-term average (30 years); APPR, application rainfall.

[b] Application rainfall window: 3 week period (1 week preceeding-2 weeks following PRE application)

[c] Soil moisture on date of PRE application

Table 4-4 Predicted GDD cumulative emergence values of foxtail barley spring seedling recruitment[a]

SITE	EC 30	EC 50	EC 80
Lethbridge 2015	246.8	286.9	380.9
Olds	314.3	341.5	403.1
Scott	245.4	371.1	585.4
Lethbridge 2016	160.5	203.9	296.1
St. Albert	309.4	338.6	404.9
Vermilion	286.8	320.7	391.3

a. estimated values in growing degree days (GDD) (Base 5°C)

Table 4-5 Parameter estimates for foxtail barley spring seedling recruitment regression

SITE	Asymptote	Growth Rate	Inflection Point	Asymptote Std Error	Growth Rate Std Error	Inflection Point Std Error
Lethbridge 2015	0.932	0.015	255.231	0.023	0.002	7.177
Olds	1.174	0.004	328.687	0.080	0.000	26.901
Scott	0.980	0.013	173.444	0.021	0.002	7.212
Lethbridge 2016	0.949	0.022	320.823	0.023	0.004	5.088
St. Albert	0.946	0.020	316.259	0.022	0.003	6.316
Vermilion	0.990	0.016	297.555	0.002	0.002	7.079

Table 4-6 Predicted GDD EC values of foxtail barley fall seedling recruitment[a]

SITE	EC 30	EC 50	EC 80
Lethbridge 2015	873.3	915.8	980.9
Olds	359.1	372.8	395.7
Scott	393.0	393.5	394.5
Lethbridge 2016	562.7	667.9	827.2
St. Albert	595.4	626.0	654.0
Vermilion	591.2	620.1	646.7

a. estimated values in growing degree days (GDD) (Base 5°C)

Table 4-7 Parameter estimates for foxtail barley fall seedling recruitment regression

SITE	Asymptote	Growth Rate	Inflection Point	Asymptote Std Error	Growth Rate Std Error	Inflection Point Std Error
Lethbridge 2015	1.049	0.019	920.636	0.067	0.003	10.725
Olds	0.991	0.062	372.549	0.029	0.010	2.898
Scott	0.937	1.684	393.425	0.017	-	0.000
Lethbridge 2016	1.061	0.008	682.777	0.065	0.001	24.170
St. Albert	-	0.017	1279.238	-	0.005	-
Vermilion	-	0.018	1218.750	-	0.005	-

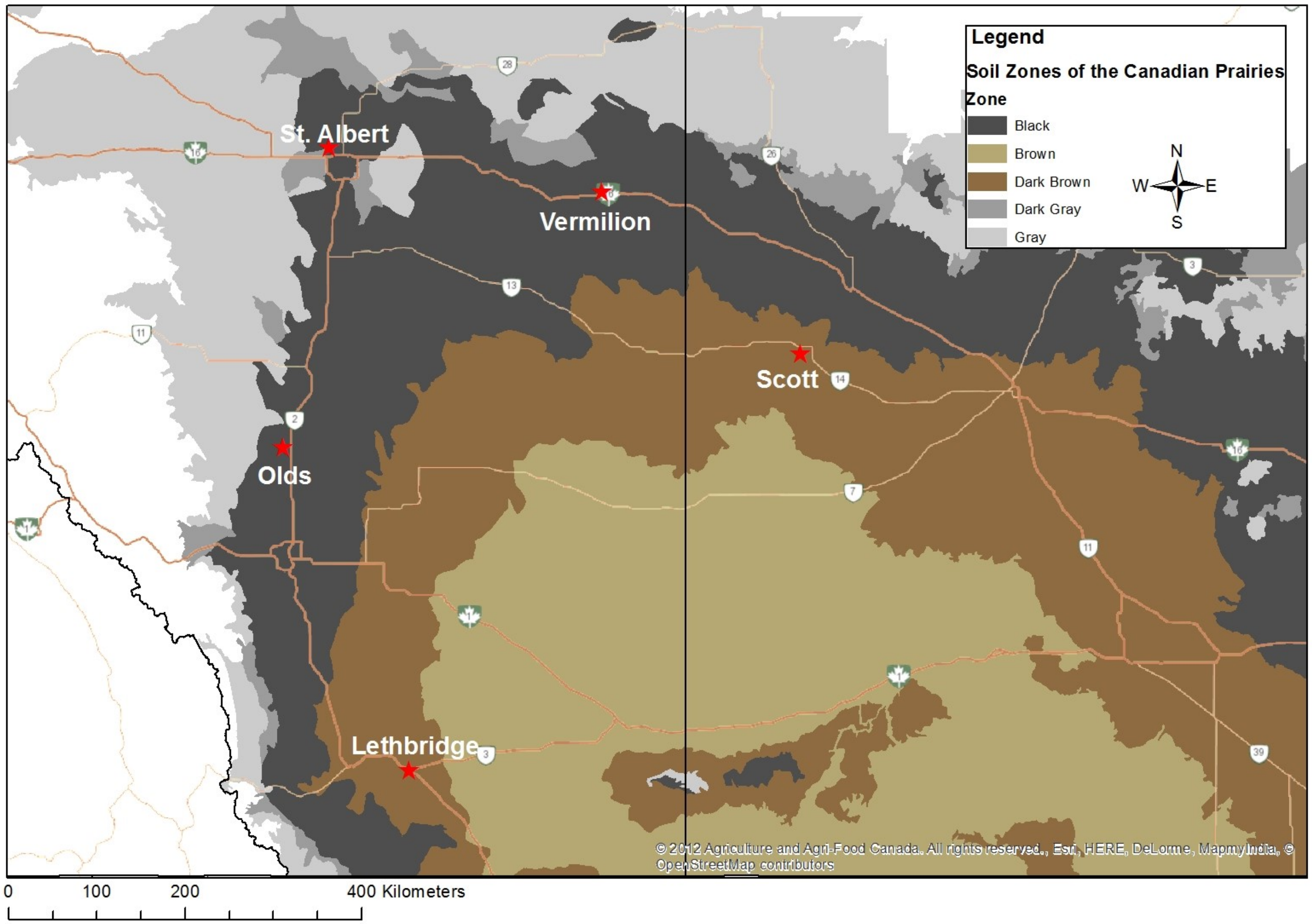
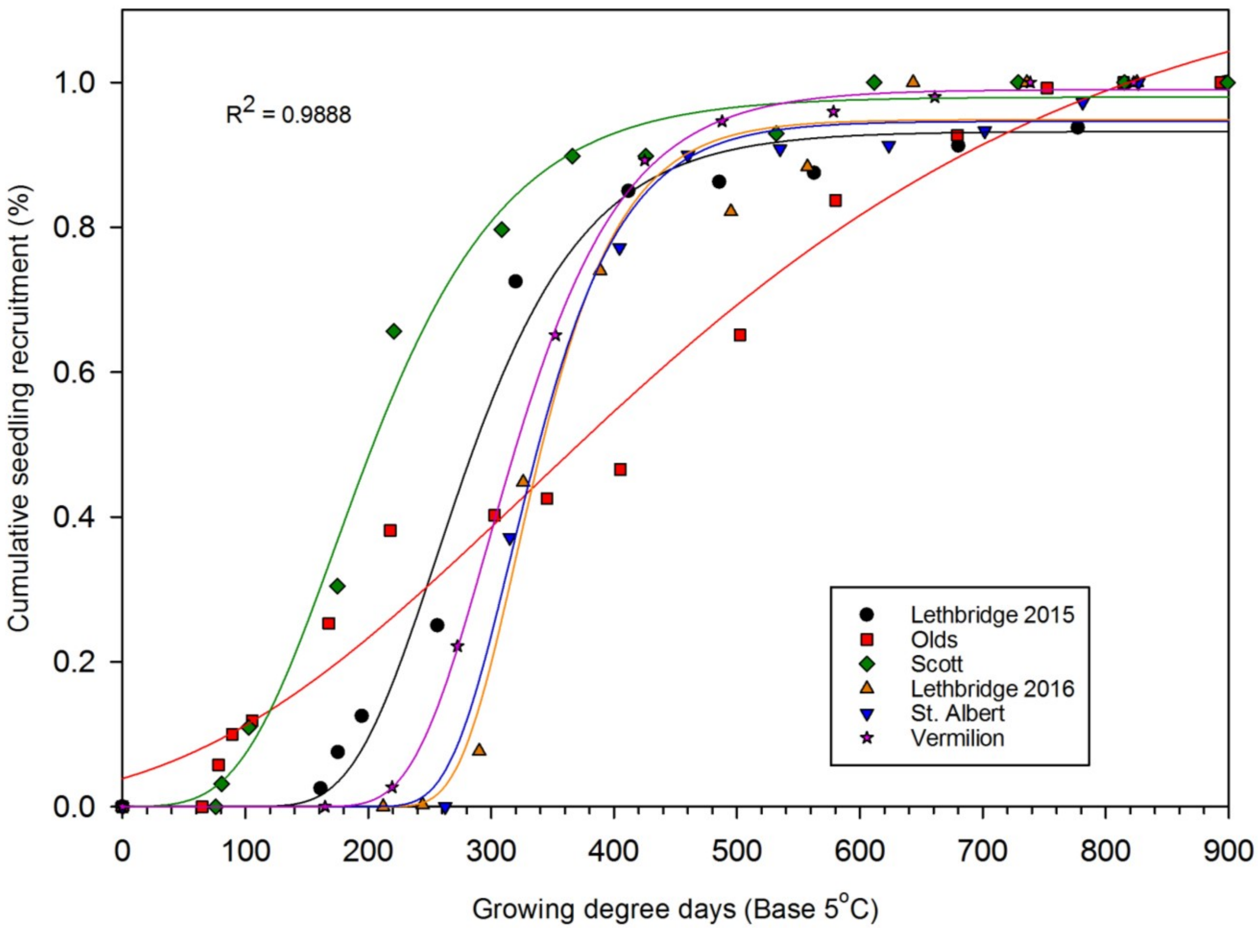
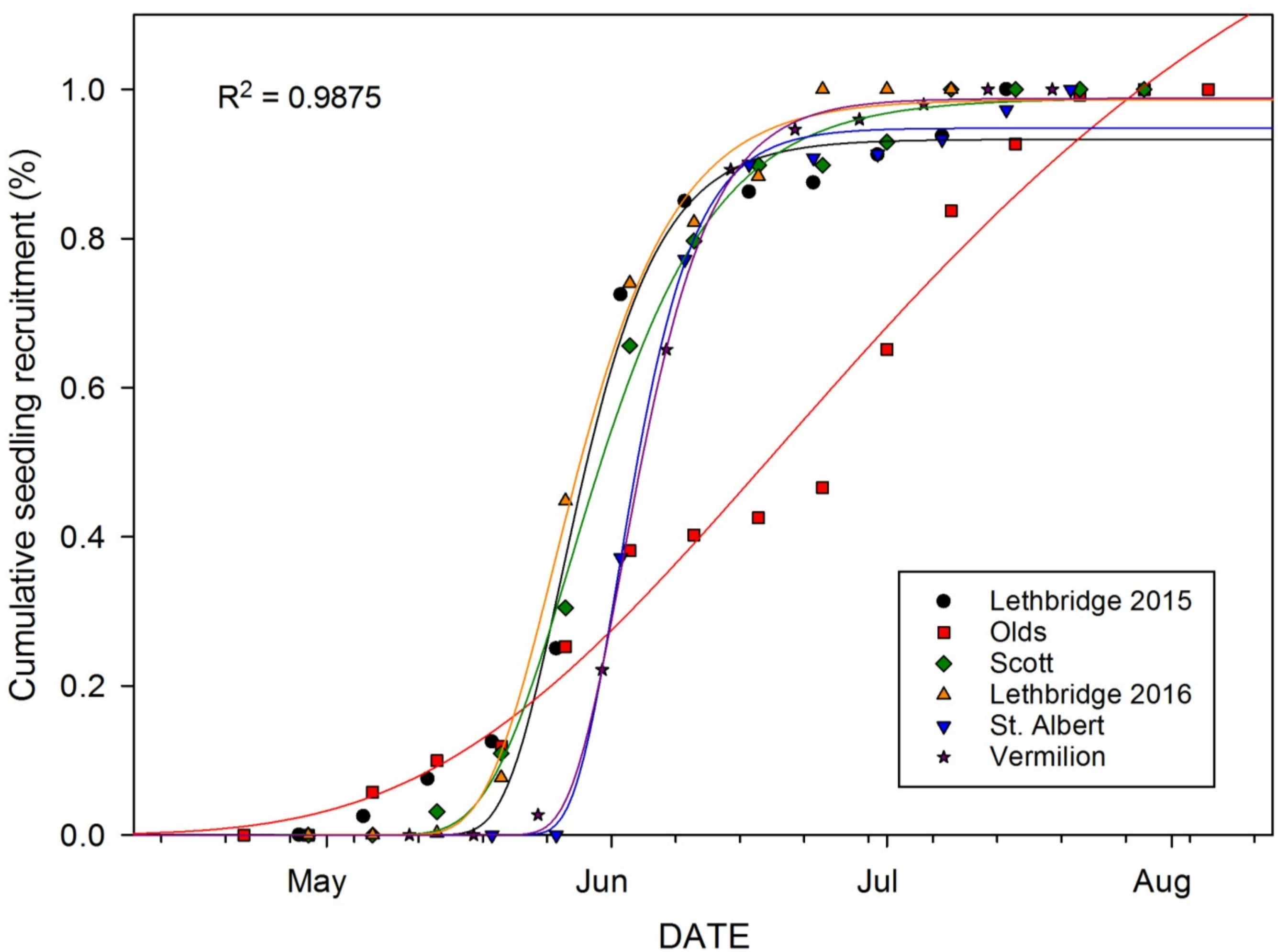

Legend
Soil Zones of the Canadian Prairies
Zone
Black
Brown
Dark Brown
Dark Gray
Gray
N
W
E
S
St. Albert
Vermilion
Scott
Olds
Lethbridge
0
100
200
400 Kilometers
© 2012 Agriculture and Agri-Food Canada. All rights reserved., Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors

Figure 4-1 2015-2016 field study locations in Alberta and Saskatchewan**.**



R^2 = 0.9888
Cumulative seedling recruitment (%)
0.0
0.2
0.4
0.6
0.8
1.0
0
100
200
300
400
500
600
700
800
900
Growing degree days (Base 5°C)
Lethbridge 2015
Olds
Scott
Lethbridge 2016
St. Albert
Vermilion

Figure 4-2 Cumulative foxtail barley spring seedling recruitment by growing degree days (GDD). Cumulative growing degree days (GDD, base 5°C) were calculated at each site beginning on January 1st of 2015 and 2016. A three parameter Gompertz regression was fit to the cumulative seedling recruitment curve for each site.



R2 = 0.9875
Cumulative seedling recruitment (%)
1.0
0.8
0.6
0.4
0.2
0.0
May
Jun
Jul
Aug
DATE
Lethbridge 2015
Olds
Scott
Lethbridge 2016
St. Albert
Vermilion

Figure 4-3 Cumulative foxtail barley spring seedling recruitment over calendar date. A three-parameter Gompertz regression was fit to the cumulative seedling recruitment curve for each site.

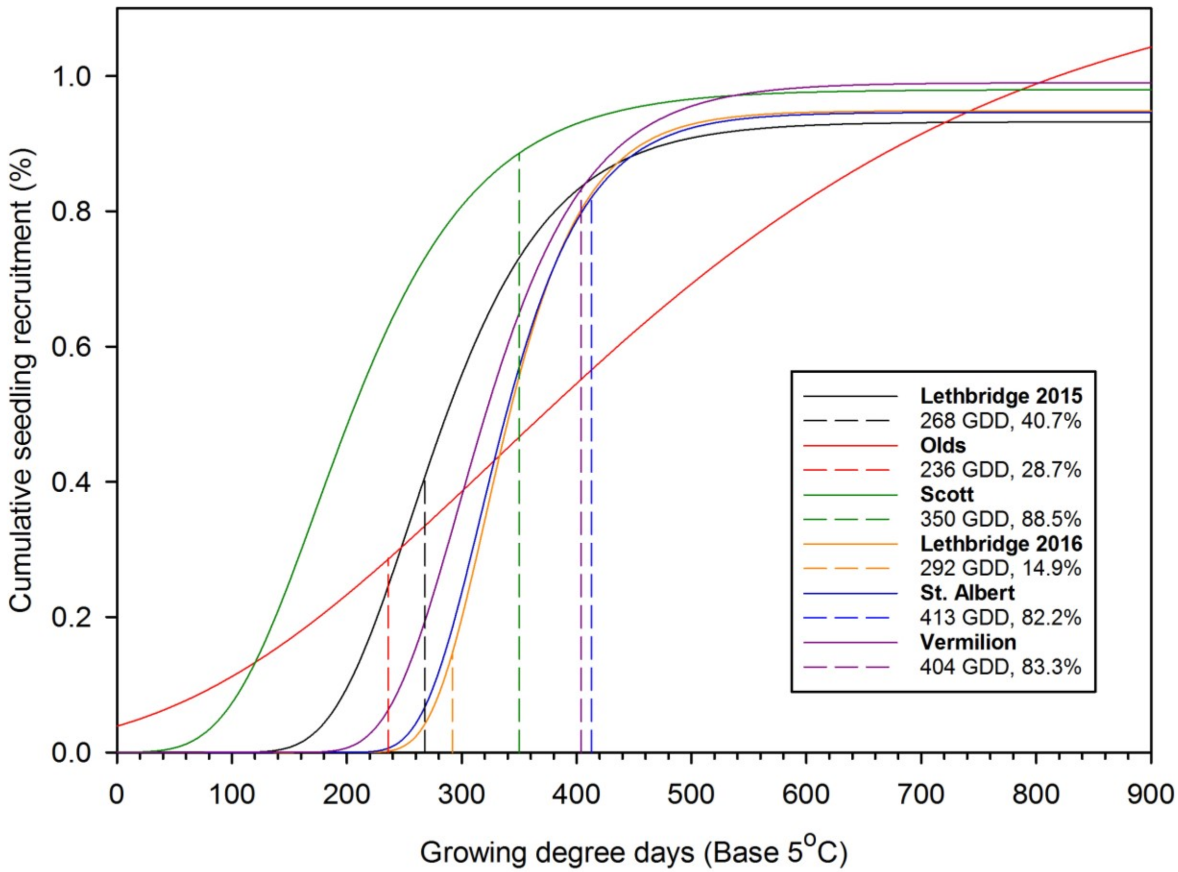
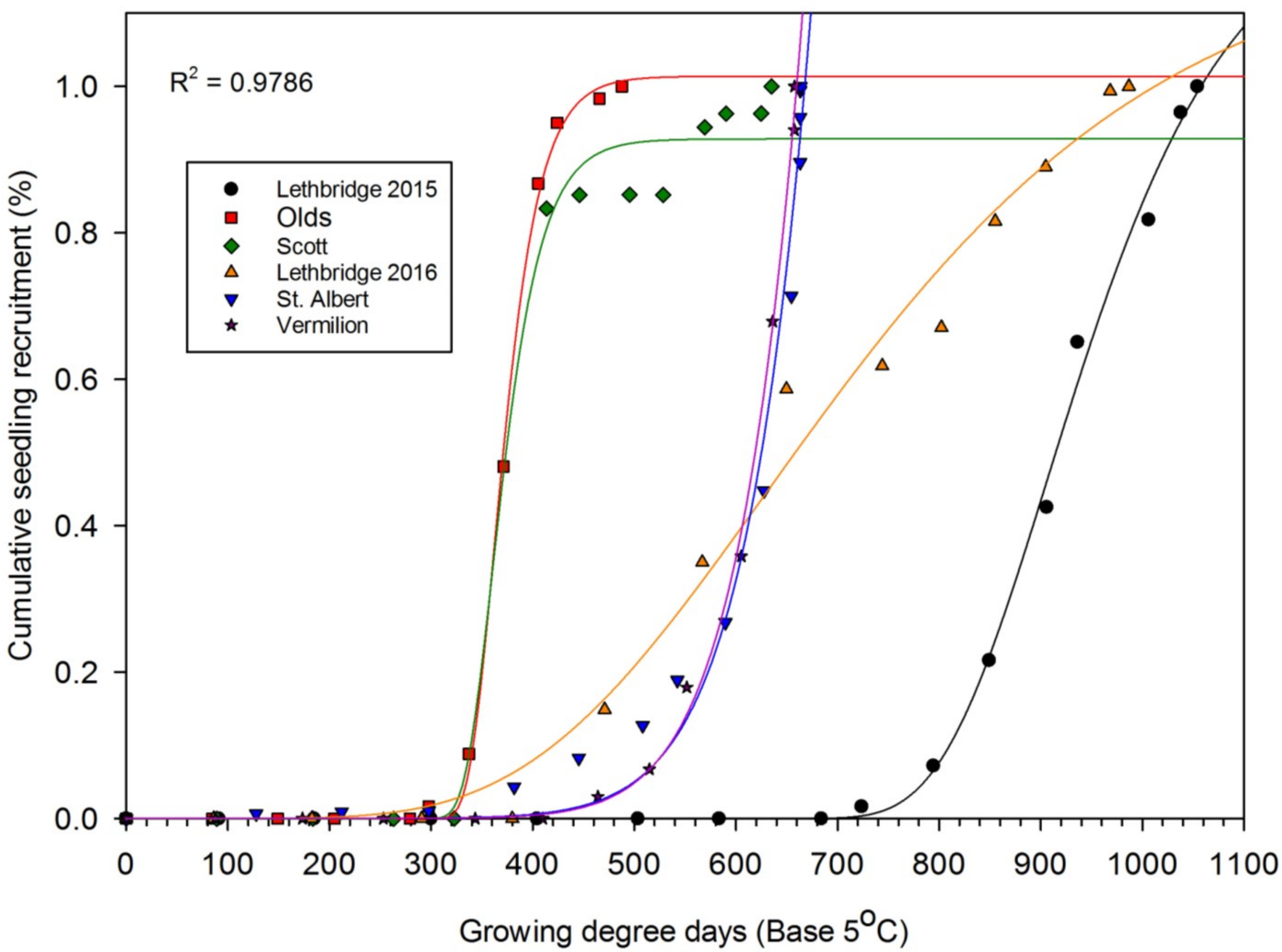


Figure 4-4 Theoretical control of spring cohort seedlings with PRE short residual herbicides. Cumulated GDDs were recorded 28

days following the PRE herbicide application dates in Table 4-2 to simulate the PRE herbicide residual control for 28 DAT. A three-parameter Gompertz regression was fit to the cumulative seedling recruitment curve for each site. The dotted lines represent potential maximum control (%) of the spring seedling cohort.



R^2 = 0.9786
Lethbridge 2015
Olds
Scott
Lethbridge 2016
St. Albert
Vermilion
Cumulative seedling recruitment (%)
0.0
0.2
0.4
0.6
0.8
1.0
0
100
200
300
400
500
600
700
800
900
1000
1100
Growing degree days (Base 5°C)

Figure 4-5 Cumulative foxtail barley fall seedling recruitment x GDD. Cumulative growing degree days (GDD, base 5°C) were calculated beginning on January 1st of 2015 and 2016. A three-parameter logistic regression was fit to the cumulative seedling recruitment curve for each site.

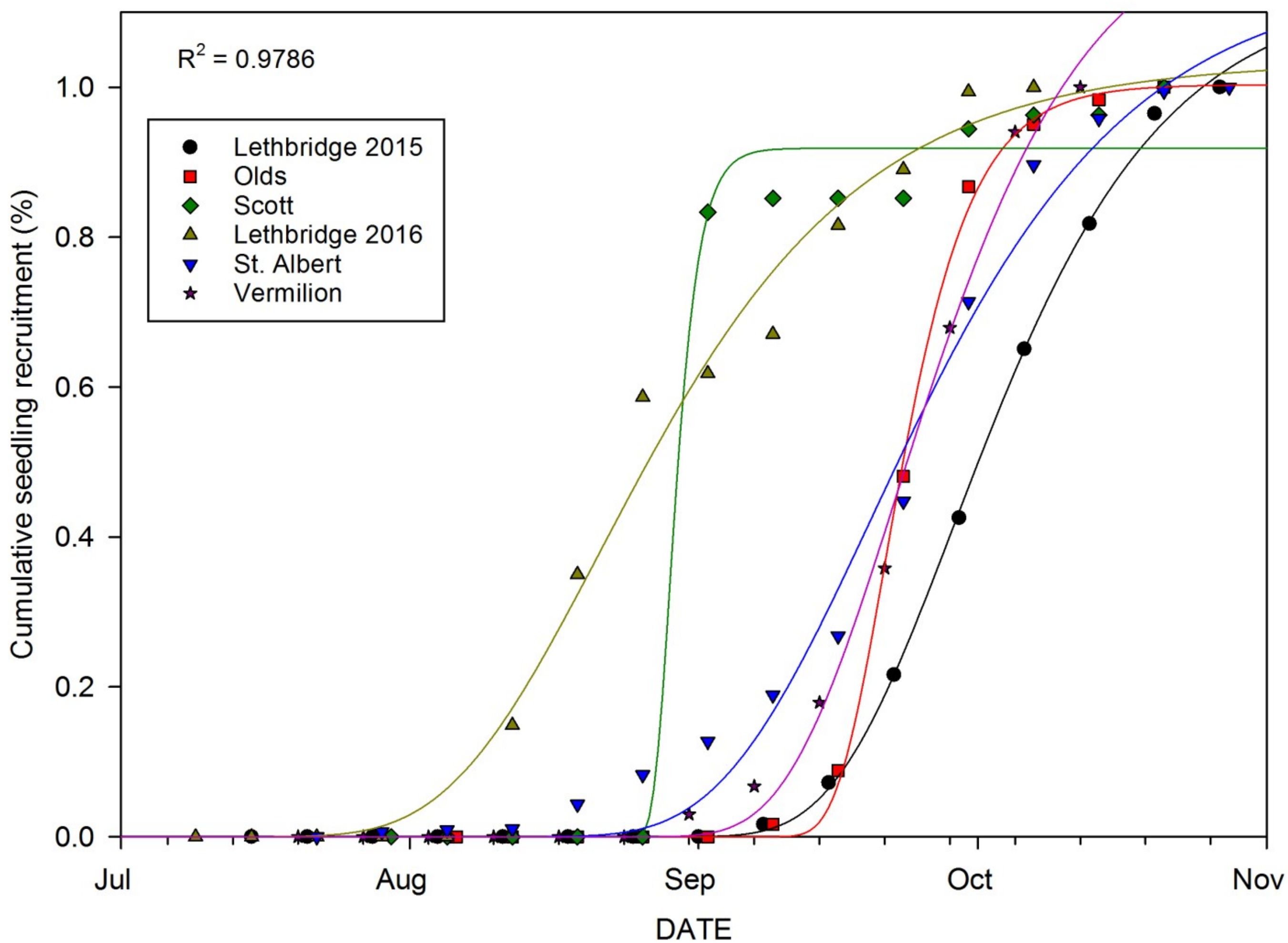

R2 = 0.9786
Lethbridge 2015
Olds
Scott
Lethbridge 2016
St. Albert
Vermilion
Cumulative seedling recruitment (%)
0.0
0.2
0.4
0.6
0.8
1.0
Jul
Aug
Sep
Oct
Nov
DATE

Figure 4-6 Cumulative foxtail barley fall seedling recruitment by calendar date. A three-parameter logistic regression was fit to the cumulative seedling recruitment curve for each site.

Chapter Five: General Discussion and Conclusions

5.1. Summary of Results

Research in this thesis supports the use of propoxycarbazone-sodium, flucarbazone-sodium/tribenuron-methyl and pyroxasulfone in combination with glyphosate (900 g ae ha^{-1}) as a PRE herbicide application prior to spring wheat, as well as a POST application of thiencarbazone to control foxtail barley. Effective combinations and timings of ALS and VLCFA herbicides in combination with glyphosate were characterised. Although effective combinations of glyphosate and ALS herbicides can control foxtail barley in most cases, recommending producers incorporate more ALS herbicide use into their rotations does not follow good herbicide rotation practices currently recommended in western Canada. Although there are no documented cases of herbicide resistance in foxtail barley populations, the use of more ALS herbicide to control a non-driver weed may have unintended impacts on other weed species in western Canada. This research supplements the research conducted by Blackshaw et al. (1999, 1999, 2000), and adds to the IWM focus of their work. New herbicides now available to producers to control foxtail barley should be integrated into the existing management strategy. Furthermore, the use of other IWM strategies such as longer crop rotations and targeted tillage could aid in controlling foxtail barley populations without more heavily relying on herbicide use. Further studies combining integrated weed management, crop rotation and tillage should be evaluated for their control on foxtail barley. Furthermore, other herbicide modes of action and active ingredients should be evaluated for their efficacy on foxtail barley.

The relationship between latitude and GDDs on foxtail barley seedling recruitment was examined. Significant foxtail barley seedling recruitment occurred in the spring, and continued into summer in some situations. A more comprehensive understanding of how soil moisture/temperature interactions and mature plant/seedling population ratios should be evaluated to provide stronger recommendations on optimal control timing of foxtail barley.

This research will support the registration of a combination of propoxycarbazone at 10 g ai ha^{-1} and glyphosate at 900 g ae ha^{-1} in spring wheat in western Canada for foxtail barley control.

5.2. Results Summarized by Research Objective

5.2.1. Determine effective rate of glyphosate required to control foxtail barley in a pre-seeding application.

In Chapter 3, trial 1, visual estimates of herbicide control found that glyphosate applied at 900 g ae ha^{-1} provided significantly greater control than 450 g ae ha^{-1} ($P < 0.0008$). However, the high rate of glyphosate did not provide significantly greater reductions in foxtail barley biomass. However, observations made throughout the study suggest that using the high rate of glyphosate is advisable to control large established plants, especially when they are water- or drought-stressed. Neither rate of glyphosate significantly reduced foxtail barley seedling recruitment when compared to the NTC. No significant differences between glyphosate rates were observed when analysing spring wheat biomass or seed yield.

5.2.2. Determine if tank-mixing a short residual product pre-seeding with glyphosate increases mature and seedling foxtail barley control.

In Chapter 3, trial 1, visual estimates of herbicide control found that the high rate of propoxycarbazone or pyroxasulfone tank-mixed with glyphosate at either the low or high rate provided significantly greater control than glyphosate applied alone at Lethbridge 2015, Vermilion and St. Albert ($P < 0.0008$, $P < 0.0056$). Pyroxasulfone was the only short residual herbicide that significantly reduced foxtail barley seedling recruitment with or without being tank-mixed with glyphosate. Propoxycarbazone and flucarbazone/tribenuron did not control seedling recruitment to the same level as pyroxasulfone, however, an observation was made that these herbicides did have activity on foxtail barley seedlings as they typically provided some control. No residual herbicides when tank-mixed with glyphosate provided significantly reduced foxtail barley biomass in comparison to applying glyphosate alone. However, a trend was observed that tank-mixing a residual herbicide with glyphosate did increase control to some degree. Although no significant differences in spring wheat yield were observed among the treatments, a trend was observed that tank-mixing a residual product with glyphosate gave small but consistent yield increases, which could potentially off-set the cost of the product compared to applying glyphosate alone.

5.2.3. Determine if efficacy of short residual herbicides varies on foxtail barley.

In Chapter 3, trial 1, the high rate of propoxycarbazone and pyroxasulfone when tank-mixed with glyphosate did provide significantly greater estimates of visual herbicide control than compared to glyphosate applied alone, whereas the low rate of propoxycarbazone and flucarbazone/tribenuron did not. However, the pre-planned non-orthogonal contrasts used in this analysis did not identify significant differences in estimates of visual herbicide control between the residual products. Likewise, pyroxasulfone provided significantly greater foxtail barley seedling reductions in comparison to glyphosate applied alone, whereas the other ALS herbicides did not. But again, the non-orthogonal contrasts did not detect any significant differences between the residual products. However, pyroxasulfone came close to providing significantly greater seedling reductions than the high rate of propoxycarbazone (0.3064). No significant differences were found between the residual products when evaluating foxtail barley biomass control.

5.2.4. Determine if tank-mixing two residual products with glyphosate provides greater control of foxtail barley than compared to one residual product.

In Chapter 3, trial 2, tank-mixing two residual herbicides with glyphosate at 900 g ae ha^{-1} was not found to provide significantly greater estimates of visual herbicide control than compared to glyphosate applied alone or when tank-mixed with one residual product. The same result was found when analysing foxtail barley biomass, however, a trend can be observed that by tank-mixing two residual products with glyphosate, it provided increased control compared to a single residual herbicide tank-mix. There were no significant differences found between tank-mixes with one or two residual products when evaluating spring wheat biomass or seed yield.

5.2.5. Determine if incorporating a PRE application of glyphosate and short residual herbicides followed by a POST application of short residual herbicide improves foxtail barley control.

In Chapter 3, trial 2, tank-mixing the high rate of propoxycarbazone with or without pyroxasulfone applied PRE with glyphosate at 900 g ae ha^{-1} followed by a POST application of thiencarbazone was found to significantly increase estimates of visual herbicide control at Scott, St. Albert, Lethbridge 2016 and Vermilion ($P < 0.0008$, $P < 0.0064$, $P < 0.0001$, $P < 0.0001$, respectively), but not at Lethbridge 2015 or Olds. Three treatments provided significantly greater reduction in foxtail barley biomass than compared to glyphosate applied alone. (1) Glyphosate +

Flucarbazone/tribenuron + pyroxasulfone; (2) Glyphosate + propoxycarbazone (7.5 g ai ha^{-1}) + pyroxasulfone followed by thiencarbazone; and (3) Glyphosate + propoxycarbazone (10 g ai ha^{-1}) + pyroxasulfone followed by thiencarbazone. No treatments provided significantly greater spring wheat biomass or seed yield beyond a single application of glyphosate at 900 g ae ha^{-1}.

5.2.6. Determine cumulative seedling recruitment of foxtail barley for the growing year.

Two cohorts of seedling recruitment occurred at all six sites, one in the spring, and again in the fall. Spring seedling recruitment typically began early-May and ceased early-July. An extended period of seedling recruitment occurred into mid-summer which contradicts the results found by Badger and Ungar (1989) and Chepil (1946). Foxtail barley seedling recruitment appears to vary by site because populations found at different latitudes expressed different patterns of emergence, suggesting that genetically isolated populations of foxtail barley show intraspecific variation compared to populations found at other latitudes. A PRE application of glyphosate is unlikely to control a large proportion of foxtail barley seedlings as they are not typically emerged at the time of application. Estimations of spring seedling control varied using short residual herbicides. Short residual herbicides applied PRE are also unlikely to control spring recruited seedlings at southern locations as a large proportion of recruitment occurs outside the window of residual control. However, short residual herbicides could be more effective at controlling seedlings at more northern locations as field operations are more delayed in the year compared to southern sites. However, at an estimated maximum level of control, 25-45% of the spring recruited seedlings would escape a PRE residual herbicide application, therefore, a POST application would need to be utilized to control the remaining population.

5.3. Future Research

Our study evaluated the short residual ALS and VLCFA herbicides applied at both a PRE and POST timing to control foxtail barley in spring wheat. Further research to expand on this study could include:

- Evaluate other PRE and POST herbicide MOAs for their efficacy on foxtail barley in spring wheat
- Further development of herbicide regimes to include the use of pre- or post-harvest glyphosate application
- Examine how multi-year crop rotations and herbicide regimes that incorporate the use of ACCase in oilseed and pulse crops affect foxtail barley populations.
- Evaluate if targeted tillage of headlands that are infested with foxtail barley is an effective method of reducing foxtail barley populations.
- Research is required to evaluate if planting desirable pasture vegetation in halophytic communities or roadsides that outcompete foxtail barley would be effective at reducing foxtail barley populations.

Works Cited

Anonymous (2006) Olympus™ 70 WDG Herbicide, Bayer CropScience, Research Triangle Pack, NC 27513

Anonymous (2008) Everest® 70 WDG Herbicide, Arysta Lifescience North America Corp., Cary, NC 27513

Awada L, Lindwall CW, Sonntag B (2014) The development and adoption of conservation tillage systems on the Canadian Prairies. Int Soil Water Conserv Res 2:47-65

Babbel GR, Wain RP (1977) Genetic structure of *Hordeum jubatum*. I. Outcrossing rates and heterozygosity levels. Can J Genet Cytol 19:143-152

Badger KS, Ungar IA (1989) The effects of salinity and temperature on the germination of the inland halophyte *Hordeum jubatum*. Can J Bot 67:1420-1425

Badger KS, Ungar IA (1990a) Seedling competition and the distribution of *Hordeum jubatum* L. along a soil salinity gradient. Functional Ecology 4:639-644

Badger KS, Ungar IA (1990b) Effects of soil salinity on growth and ion content of the inland halophyte *Hordeum jubatum*. Bot Gaz 151:314-321

Badger KS, Ungar IA (1991) Life history and population dynamics of *Hordeum jubatum* along a soil salinity gradient. Can J Bot 69:384-393

Badger KS, Ungar IA (1994) Seed bank dynamics in an inland salt marsh, with special emphasis on the halophyte *Hordeum jubatum* L.. Int J Plant Sci 155:66-72

Banting JD (1979) Germination, emergence and persistence of foxtail barley. Can J Plant Sci 59:35-41

Baskin CC, Baskin JM (1988) Germination ecophysiology of herbaceous plant species in a temperate region. Am J Bot 75:286-305

Beckie HJ (2006) Herbicide-resistant weed management: focus on glyphosate. Pest Manag Sci 67:1037-1048

Beckie HJ, Harker KN, Hall LM, Warwick SI, Légère A, Sikkema PH, Clayton GW, Tomas AG, Leeson JY, Séguin-Swartz G, Simard M-J (2006) A decade of herbicide-resistant crops in Canada. Can J Plant Sci 86:1243-1264

Beckie HJ, Harker KN, Hall LM, Holm FA, Gulden RH (2011) Risk assessment of glyphosate resistance in western Canada. Weed Technol 25:159-164

Beckie HJ, Leeson JY, Thomas AG, Hall LM, Brenzil CA (2008) Risk assessment of weed resistance in the Canadian Prairies. Weed Technol 22:741-746

Beres BL, Harker KN, Clayton GW, Bremer E, Blackshaw RE, Graf RJ (2010) Weed-competitive ability of spring and winter cereals in the northern Great Plains. Weed Technol 24:108-116

Best KF, Banting JD, Bowes GG (1978) The biology of Canadian weeds. 31. *Hordeum jubatum* L. Can J Plant Sci 58:699-708

Blackshaw RE, Brandt RN, Janzen HH, Entz T, Grant CA, Derksen DA (2003) Differential response of weed species to added nitrogen. Weed Sci 51:532-539

Blackshaw RE, Semach G, Entz T (1998) Postemergence control of foxtail barley (*Hordeum jubatum*) seedlings in spring wheat (*Triticum aestivum*) and flax (*Linum usitatissimum*). Weed Technol 12:610-616

Blackshaw RE, Semach G, Li X, O'Donovan JT, Harker KN (1999) An integrated weed management approach to managing foxtail barley (*Hordeum jubatum*) in conservation tillage systems. Weed Technol 13:347-353

Blackshaw RE, Semach G, Li X, O'Donovan JT, Harker KN (2000) Tillage, fertilizer and glyphosate timing effects on foxtail barley (*Hordeum jubatum*) management in wheat. Can J Plant Sci 80:655-660

Blackshaw RE, Harker KN, O'Donovan JT, Beckie HJ, Smith EG (2008) Ongoing development of integrated weed management systems on the Canadian Prairies. Weed Sci 56:146-150

Blackshaw RE, Larney RO, Lindwall CW, Kozub GC (1994) Crop rotation and tillage effects on weed populations on the semi-arid Canadian Prairies. Weed Technol 8:231-237

Blouch RM (1953) Grass herbicides in today's agricultural economy. The Scientific Monthly 76:36-41

Blumenthal D, Jordan N (2001) Weeds in field margins: a spatially explicit simulation analysis of Canada thistle population dynamics. Weed Sci 49:509-519

Böger P, Matthes B, Schmalfuss J (2000) Towards the primary target of chloroacetamides-new findings pave the way. Pest Manag Sci 56:497-508

Bolduc R, Comeau A, Couture L, St-Pierre CA (1988) Resistance to alternating freeze and thaw stresses in wheat, rye, triticale and foxtail barley. Can J Plant Sci 68:331-335

Bowes GG (1984) Use of propyzamide to control foxtail barley in Russian wild ryegrass. Can J Plant Sci 64:725-730

Boyd NS, Van Acker RC (2003) The effects of depth and fluctuating soil moisture on the emergence of eight annual and six perennial plant species. Weed Sci 51:725-730

Braidek JT, Fedec P, Jones D (1984) Field survey of halophytic plants of disturbed sites on the Canadian prairies. Can J Plant Sci 64:745-751

Brandt, SA (1992) Zero vs. conventional tillage and their effects on crop yield and soil moisture. Can J Plant Sci 72:679-688

Brown WM, Velasco VR, Hill JP, Dillon MA (1993) Barley stripe rust, *Puccinia striiformis*, found in Colorado. Phytopathology 39:367-384

Brust GE, House GJ (1988) Weed seed destruction by arthropods and rodents in low-input soybean agroecosystems. Am J Alternative Agric 3:19–25

Campbell CA, Zentner RP, Gameda S, Blomert B, Wall DD (2002) Production of annual crops on the Canadian prairies: Trends during 1976-1998. Can J Plant Sci 82:45-57

Cardina JC, Norquay HM, Stinner BR, McCartney DA (1996) Postdispersal predation of velvetleaf (*Abutilon theophrasti*) seeds. Weed Sci 44:534–539

Casely JC, Coupland D (1985) Environmental and plant factors affecting glyphosate uptake, movement and activity. Pages 92-124 *in* Grossbard E, Atkinson D, eds. The herbicide Glyphosate. Butterworth Publishers, London, UK.

[CFIA] Canadian Food Inspection Agency (2017) Weed Seeds Order. Ottawa, ON: http://www.inspection.gc.ca/plants/seeds/weed-seeds-order/eng/1463453027786/1463453028410 Accessed January 18, 2017

Chandler K, Murphy SD, Swanton CJ (1994) Effect of tillage and glyphosate on control of quackgrass (*Elytrigia repens*). Weed Technol 8:450-456

Chepil WS (1946) Germination of weed seeds. 1. Longevity, periodicity of germination, and vitality of seeds in cultivated soil. Sci Agric 26:307-346

Collins BA, Fowler DB (1996) Effect of soil characteristics, seeding depth, operating speed, and opener design on draft force during direct seeding. Soil and Tillage Res 39:199-211

Comeau A, Fedak G, St-Pierre CA, Cazeault R (1988) Intergenetic hybrids between *Hordeum jubatum* (4x) and *Triticum aestivum* (6x). Genome 30:245-249

Conn JS, Deck RE (1995a) Seed viability and dormancy of 17 weed species after 9.7 years of burial in Alaska. Weed Sci 43:583-585

Conn JS, Deck RE (1995b) Optimal glyphosate application time for control of foxtail barley (*Hordeum jubatum*). Weed Technol 9:267-269

Cords HP (1960) Factors affecting the competitive ability of foxtail barley (*Hordeum jubatum*). Weeds 8:636-644

Curtis BC (2002) Wheat in the World. Pages 1-17 *in* Curtis BC, Rajaram S, Macpherson, HG, eds. Bread wheat: Improvement and production. FAO, Rome

DePauw RM, Knox RE, Humphreys DG, Thomas JB, Fox SL, Brown PD, Singh AK, Pozniak C, Randhawa HS, Fowler DB, Graf RJ, Hucl P (2011) New breeding tools impact Canadian commercial farmer fields. Czech J Genet Plant Breed 47:28-34

Derksen DA, Lafond GP, Thomas AG, Loeppky HA, Swanton CJ (1993) Impact of agronomic practices on weed communities: Tillage systems. Weed Sci 41:409-417

Derksen DA, Thomas AG, Lafond GP, Loeppky HA, Swanton CJ (1994) Impact of agronomic practices in weed communities: Fallow within tillage systems. Weed Sci 42:184-194

Derksen DA, Anderson RL, Blackshaw RE, Maxwell B (2002) Weed dynamics and management strategies for cropping systems in the northern Great Plains. Agron J 94:174-185

Derpsch R (2003) Conservation tillage, no-tillage and related technologies. Chapter 4. Pages 181-190 *in* Conservation Agriculture. Derpsch R eds. García-Torres L, Benites J, Martínez-Vilela A, Holgado-Cabrera A, Springer Netherlands

Derpsch R, Friedrich T, Kassam A, Hongwen L (2010) Current status of adoption of no-till farming in the world and some of its main benefits. Int J Agric and Biol Eng 3:-25

de Ruiter H, Meinen E (1998) Influence of water stress and surfactant on the efficacy, absorption, and translocation of glyphosate. Weed Sci 46:289-296

Dodd JD, Coupland RT (1966) Vegetation of saline areas in Saskatchewan. Ecology 47:958-968

Donald WW (1987) Established foxtail barley control in spring, 1985. Res Rep North Cent Weed Control Conf 44:298

Donald WW (1988) Established foxtail barley, *Hordeum jubatum*, control with glyphosate plus ammonium sulfate. Weed Technol 2:364-368

Donald WW (1990) Primary tillage for foxtail barley (*Hordeum jubatum*) control. Weed Technol 4:318-321

Egley GH, Williams RD (1990) Decline of weed seeds and seedling emergence over five years as affected by soil disturbance. Weed Sci 38:504–510

Eliason R, Schoenau JJ, Szmigielski AM, Laverty WM (2004) Phytotoxicity and persistence of flucarbazone-sodium in soil. Weed Sci 52:857-862

Franz JE, Mao MK, Sikorski JA (1997) Glyphosate: a unique global herbicide. Am Chem Soc

Froud-Williams RJ, Chancellor RJ, Drennan SH (1981) Potential changes in weed floras associated with reduced-cultivation systems for cereal production in temperate regions. Weed Res 21:99-109

Gaines TA, Barker AL, Patterson EL, Westra P, Westra EP, Wilson RG, Kniss AR (2016) Prediction of glyphosate resistance level based on EPSPS gene copy number in *Kochia scoparia*. bioRxiv: 047878

Gates FC (1940) Flora of Kansas. Agric Exp Sta, Kansas Coll Agric and Appl Sci, Topeka, Kansas. p 266

Garthwaite AJ, von Bothmer R, Colmer TD (2005) Salt tolerance in wild *Hordeum* species is associated with restricted entry of Na^+ and Cl^- into the shoots. J Exp Bot 56:2365-2378

Geier PW, Stahlman PW, Hargett JG (2001) Dose responses of weeds and winter wheat to MKH 6561. Weed Sci 49:788-791

Geier PW, Stahlman PW, Peterson DE, Miller SD (2002) Application timing affects BAY MKH 6561 and MON 37500 efficacy and crop response in winter wheat. Weed Technol 16:800-806

Glenn EP, Brown JJ, Blumwald E (1999) Salt tolerance and crop potential of halophytes. Critical Reviews in Plant Science 18:227-255

Gossen BD, Turnbull GD (1995) Head smut (*Ustilago bullata*) of grasses on the Canadian prairies: Distribution, impact, and control. Can J Plant Pathol 17:49-56

Government of Alberta (2016) Alberta crop production statistics. Edmonton, AB: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sdd12061 Accessed January 12, 2017

Gray RS, Taylor JS, Brown WJ (1996) Economic factors contributing to the adoption of reduced tillage technologies in central Saskatchewan. Can J Pant Sci 76:661-668

Guérif J, Richard G, Machet JM, Recous S, Roger-Estrade J (2001) A review of tillage effects on crop residue management, seedbed conditions and seedling establishment. Soil Tillage Res 61:13-32

Hamman WM and Wilson DB (1977) Fall application of pronamide for selective control of foxtail barley in pasture. Proc Ann Meeting North Central Weed Cont Conf 32:61

Heap I (2017) The international survey of herbicide resistant weeds: http://www.weedscience.org/ Accessed January 25, 2017

Hoffman ML, Owen MDK, Buhler DD (1998) Effects of crop and weed management on density and vertical distribution of weed seeds in soil. Agron J 90:793–799

Hume L, Archibold OW (1986) The influence of a weedy habitat on the seed bank of an adjacent cultivated field. Can J Bot 64:1879-1883

Iqbal M, Moakhar NP, Strenzke K, Haile T, Pozniak C, Hucl P, Spaner D (2016) Genetic improvement in grain yield and other traits of wheat grown in western Canada. Crop Sci 56:613-624

Israelsen KR (2009) Herbicide, salinity, and flooding tolerance of foxtail barley (*Hordeum jubatum* L.) and desirable pasture grasses. Dissertation. Utah State University, Logan UT

Israelsen KR, Ransom CV, Waldron BL (2011) Salinity tolerance of foxtail barley (*Hordeum jubatum*) and desirable pasture grasses. Weed Sci 59:500-505

Jackson BE (2007) Foxtail barley (*Hordeum jubatum*) control with propoxycarbazone-sodium and fluazifop-p-butyl in three Alaska native grass species. Dissertation. University of Alaska Fairbanks, Fairbanks, AK

Johnson RG, Ali MB (1982) Economies of wheat-fallow cropping systems in western North Dakota. Western J Agric Econ 7:67-78

Kaundun SS (2014) Resistance to acetyl-CoA carboxylase-inhibiting herbicides. Pest Management Science 70:1405-1417

Keiffer CH, Ungar IA (1997) The effects of density and salinity on shoot biomass and ion accumulation in five inland halophytic species. Can J Bot 75:96-107

Kenkel NC, McIlraith AL, Burchill CA, Jones G (1991) Competition and the response of three plant species to a salinity gradient. Can J Bot 69:2497-2502

Kirkland KJ, Johnson EN, Stevenson FC (2001) Control of wild oat (*Avena fatua*) in wheat with MKH 6562. Weed Technol 15:48-55

Koskinen WC, McWhorter CG (1986) Weed control in conservation tillage. J Soil Water Conservation 41:365-370Lafond GP, Derksen DA (1996) Long-term potential of conservation tillage on the Canadian prairies. Can J Plant Pathol 18:151-158

Lafond GP, Zentner RP, Geremia R, Derksen DA (1993) The effects of tillage systems on the economic performance of spring wheat, winter wheat, flax and field pea production in east-central Saskatchewan. Can J Plant Sci 73:47-54

Leeson JY, Thomas AG, Hall LM, Brenzil CA, Andrews T, Brown KR, Van Acker RC (2005) Prairie weed surveys of cereal, oilseed and pulse crops from the 1970s to the 2000s. Weed Survey Series Publication 05-1CD. Agriculture and Agri-Food Canada, Saskatoon Research Centre, Saskatoon, Saskatchewan

Leeson JY, Neeser C, Kimmel N, Vadnais M (2012) Alberta weed survey of dryland crops in 2010. Weed Survey Series Publication 12-1. Agriculture and Agri-Food Canada, Saskatoon Research Centre, Saskatoon, Saskatchewan

Leeson JY (2016) Residual weed population shifts in Saskatchewan-1976 to 2015. Poster. 2016 CWSS Annual Meeting, Moncton, NB. Published: Agriculture and Agri-Food Canada, Saskatoon Research Centre, Saskatoon, Saskatchewan

Lindwall CW, Anderson DT (1981) Agronomic evaluation of minimum tillage systems for summer fallow in southern Alberta. Can J Plant Sci 61:247-253

Malhi SS, Mumey G, O'Sullivan PA, Harker KN (1988) An economic comparison of barley production under zero and conventional tillage. Soil and Tillage Research 11:159-166

Mangin AR, Hall LM, Schoenau JJ, Beckie HJ (2017) Influence of tillage on control of wild oat (*Avena fatua*) by the soil-applied herbicide pyroxasulfone. Weed Sci 1-9

McCaig TN, DePauw RM (1995) Breeding hard red spring wheat in western Canada: Historical trends in yield and related variables. Can J Plant Sci 75:387-393

McCallum BD, DePauw RM (2008) A review of wheat cultivars grown in the Canadian prairies. Can J Plant Sci 88:649-677

Mohler CL (2001) Mechanical management of weeds. *in* Liebman M, Mohler CL, Staver CP, eds: Ecological management of agricultural weeds. Pages 139-209, Cambridge University Press, Cambridge, UK

Moyer JR, Roman ES, Lindwall CW, Blackshaw RE (1994) Weed management in conservation tillage systems for wheat production in North and South America. Crop Protection 13:243-259

Mulligan GA, Findlay JN (1970) Reproductive systems and colonization in Canadian weeds. Can J Bot 48:859-860

O'Donovan JT, Blackshaw RE, Harker KN, McAndrew DW, Clayton GW (2001) Canada thistle (*Cirsium arvense*) management in canola (*Brassica rapa*) and barley (*Hordeum vulgare*) rotations under zero tillage. Can J Plant Sci 81:183-190

O'Donovan JT, Blackshaw RE, Harker KN, Clayton, GW, Moyer JR, Dosdall LM, Maurice DC, Turkington TK (2007) Integrated approaches to managing weeds in spring-sown crops in western Canada. Crop Prot 26:390-398

Olson BLS, Zollinger RK, Thompson CR, Peterson DE, Jenks B, Moechnig M, Stahlman PW (2011) Pyroxasulfone with and without sulfentrazone in sunflower (*Helianthus annuus*). Weed Technol 25:217-221

Ostlie MH, Howatt KA (2013) Downy brome (*Bromus tectorum*) competition and control in no-till spring wheat. Weed Technol 27:502-508

Peterson DP, Thompson CR, Regehr DL, Al-Khatib K (2001) Herbicide Mode of Action. Ext Pub C-175 Kansas State Univ AG Exp Sta and Coop Ext Service

R Core Team (2013). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/

Ray TB (1984) Site of action of chlorsulfuron. Plant Physiology 75:827-831

Reddy SS, Stahlman PW, Geier PW (2013) Downy brome (*Bromus tectorum* L.) and broadleaf weed control in winter wheat with acetolactate synthase-inhibiting herbicides. Agron J 3:340-348

Reidy ME, Swanton CJ (1994) Postemergence control of quackgrass [*Elytrigia repens* (L.) Nevski] with DPX-79406 in corn (*Zea mays* L.). Can J Plant Sci 74:375-381

Sanford GB, Broadfoot WC (1933) The relative susceptibility of cultivated and native hosts in Alberta to stripe rust. Sci Agric 13:714-21

Saskatchewan Ministry of Agriculture (2016) Guide to Crop Protection: Weeds, Plant Diseases, Insects. Saskatchewan Ministry of Agriculture, Regina, SK: https://www.saskatchewan.ca/business/agriculture-natural-resources-and-industry/agribusiness-farmers-and-ranchers/crops-and-irrigation/crop-protection/guide-to-crop-protection Accessed January 18, 2017

Shearer BL, Skovmand B, Wilcoxson RD (1977) *Hordeum jubatum* as a source of inoculum of *Septoria avenae* f. sp. triticea and *S. passerinii*. Phytopathology 67:1338-1341

Senseman SA, editor (2007) Herbicide handbook. Ninth ed. Lawrence, KS: Weed Science Society of America

Smith LM, Kadlec JA (1983) Seed banks and their role during drawdown of a North American marsh. J Appl Ecol 20:673-684

[StatsCan] Statistics Canada (2014) Census of agriculture, tillage practices used to prepare land for seeding. Ottawa, ON: http://www5.statcan.gc.ca/cansim/a26 Accessed January 12, 2017

[StatsCan] Statistics Canada (2015) Canadian grain exports (annual). Ottawa, ON: http://www.statcan.gc.ca/daily-quotidien/151204/cg-c001-eng.htm. Accessed January 12, 2017

[StatsCan] Statistics Canada (2016a) Grain varieties by acreage insured. Ottawa, ON: https://www.grainscanada.gc.ca/statistics-statistiques/variety-variete/varieties-en.htm. Accessed January 12, 2017

[StatsCan] Statistics Canada (2016b) Estimated areas, yield, production and average farm price of principal field crops, in metric units. Ottawa, ON: http://www5.statcan.gc.ca/cansim/a26?lang=eng&id=10071 Accessed January 12, 2017

Steinrücken HC, Amrhein N (1980) The herbicide glyphosate is a potent inhibitor of 5-enolpyruvylshikimic acid-3-phoshate synthase. Biochemical and Biophysical Research Communications 94:1207-1212

Szmigielski AM, Schoenau JJ, Irvine A, Schilling B (2008) Evaluating a mustard root-length bioassay for predicting crop injury from soil residual flucarbazone. Communications in Soil Science and Plant Analysis 39(3-4):413-420

Szmigielski AM, Schoenau JJ, Johnson EN, Holm FA, Sapsford KL (2012) Determination of thiencarbazone in soil by oriental mustard root length bioassay. Weed Sci 60:468-473

Tanetani Y, Kaku K, Kawai K, Fujioka T, Shimizu T (2009) Action mechanism of a novel herbicide, pyroxasulfone. Pestic Biochem Physiol 95:47-55

Tessier S, Peru M, Dyck FB, Zentner FP, Campbell CA (1990) Conservation tillage for spring wheat production in semi-arid Saskatchewan. Soil Tillage Res 18:73-89

Thomas JB, Graf RJ (2014) Rates of yield gain of hard red spring wheat in western Canada. Can J Plant Sci 94:1-13

Thompson K, Grime JP (1979) Seasonal variation in the seed banks of herbaceous species in ten contrasting habitats. J Ecol 67:893-921

Tidemann BD, Hall LM, Johnson EN, Beckie HJ, Sapsford KL, Raatz LL (2014) Efficacy of fall- and spring-applied pyroxasulfone for herbicide-resistant weeds in field pea. Weed Technol 28:351-360

Tiessen KHD, Elliot JA, Yarotski J, Lobb DA, Flaten DN, Glozier (2010) Conventional and conservation tillage: Influence on Seasonal runoff, sediment, and nutrient losses in the Canadian Prairies. J Environ Qual 39:964-980

Ungar IA (1974) The effect of salinity and temperature on seed germination and growth of *Hordeum jubatum*. Can J Bot 52:1357-1362

Ungar IA (1978) Halophyte seed germination. Bot Rev 44:233-264

Ungar IA (1982) Germination ecology of halophytes. Page 143-154 *in* Tasks for vegetation science. eds. Sen DN, Rajpurohit KS. Dr. W Junk Publishers, Dordrecht, Netherlands

Ungar IA, Riehl T (1980) The effect of seed reserves on species composition in zonal halophyte communities. Bot Gaz 141:447-452

Ungar IA (2001) Seed banks and seed population dynamics of halophytes. Wetlands Ecology and Management 9:499-510

[USDA, NRCS] United States Department of Agriculture Natural Resources Conservation Service (2017) https://plants.usda.gov/core/profile?symbol=HOJU Accessed January 18, 2017

Van Acker RC (2009) Weed biology serves practical weed management. Weed Research 49:1-5

Violett RD (2012) Ecology and control of foxtail barley (Hordeum jubatum L.) on irrigated pastures in the Big Horn Basin, Wyoming. Dissertation. University of Wyoming, Laramie, WY

Westra E, Shaner D, Westra P, Chapman P (2014) Dissipation and leaching of pyroxasulfone and S-metolachlor. Weed Technol 28:72-81

Whaley CM, Wilson HP, Westwood, JH (2007) A new mutation in plant ALS confers resistance to five classes of ALS-inhibiting herbicides. Weed Sci 55:83-90

Wiersma AT, Gaines TA, Preston C, Hamilton JP, Giacomini D, Buell CR, Leach JE, Westra P (2015) Gene amplification of 5-enol-pyruvylshikimate-3-phosphate synthase in glyphosate-resistant *Kochia scoparia*. Planta 241:463-474

Wilson DB (1967) Growth of *Hordeum jubatum* under various soil conditions and degrees of plant competition. Can J Plant Sci 47:405-412

Wilson RG, Michiels A (2003) Fall herbicide treatments affect carbohydrate content in roots of Canada thistle (Cirsium arvense) and dandelion (*Taraxacum officinale*). Weed Sci 51:299-304

Witt WW (1984) Response of weeds and herbicides under no-tillage conditions. Chapter 7 Pages 153-170 *in* No-Tillage Agriculture. Phillips RE, Phillips SH eds. Van Nostrand Reinhold Company, New York

Wruke MA, Arnold WE (1985) Weed species distribution as influenced by tillage and herbicides. Weed Sci 33:853-856

[WSSA] Weed Science Society of America (2017) Herbicide Mechanism of Action (MOA) Classification List: http://wssa.net/wp-content/uploads/WSSA-Herbicide-MOA-20160911.pdf Accessed January 23, 2017

Zentner RP, Wall DD, Nagy CN, Smith EG, Young DL, Miller PR, Campbell CA, McConkey BG, Brandt SA, Lafond GP, Johnston AM, Derksen DA (2002) Economics of crop diversification and soil tillage opportunities in the Canadian prairies. Agron J 94:216-230