University of Alberta

Wild oat (*Avena fatua* L.) population dynamics within integrated weed management systems

by

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A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science
in
Plant Science

Department of Agricultural, Food and Nutritional Science

Spring 2011
Edmonton, Alberta

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Dedication

“Our greatest weakness lies in giving up. The most certain way to succeed is always to try just one more time” – Thomas Edison

Abstract

Integrating cultural weed management practices with herbicides is an important strategy to reduce wild oat (*Avena fatua* L.) populations in Alberta, Canada. The purpose of this thesis is to expand the knowledge on wild oat seed banks and seedling emergence within integrated weed management systems. Field experiments were conducted from 2006-2007 to examine the impact of crop rotation, barley cultivar, barley seeding rate and herbicide rate on wild oat seed bank density, seed mortality, seedling emergence and seedling survivorship. Management systems consisting of diverse crop rotations, tall barley cultivars and increased barley seeding rates reduced wild oat seed bank density, seedling emergence and seedling survivorship, especially at low herbicide rates. Wild oat seed banks predicted subsequent wild oat emergence, whereas biomass and emergence strongly predicted seed banks. Lastly, 50% wild oat emergence was achieved at 537 and 509 growing degree days in 2006 and 2007, respectively, in Lacombe, Alberta.

Acknowledgements

I would like to formally thank my supervisor, Dr. Linda Hall, for her expertise, patience and mentorship during this entire thesis process. I would also like to acknowledge my thesis committee, Dr. Neil Harker, Dr. Edward Bork and Dr. Ellen Macdonald for providing me with valuable knowledge and continuous support on completion of this thesis. Thank you to Dr. John O'Donovan and Dr. George Clayton for the opportunity to collaborate on Test 42. As well, a special thank you to Drs. Alex Pswarayi and Craig Stevenson, for their statistical support, advice and encouragement.

I would like to acknowledge the technical staff from the University of Alberta, Keith Topinka, Debby Topinka, Jamie Crowe, Cara Kozack, Sue Jess and Cliff Theroux. A special thank you to Judy Irving whom spent many long hours processing wild oat seeds from the soil and in the lab.

I would also like to thank the technical staff Larry Michielson, Jennifer Zuidof, Patty Reid, Greg Semach and Joe Unruh from the Lacombe, Beaverlodge and Fort Vermillion AAFC research stations.

I would like to acknowledge my fellow grad students Dr. Marc McPherson, Ryan Nielson, Dr.Amit Jhala, Vanessa Kavanagh and most specially Dr. Jody Dexter, Janet Montgomery, Lisa Raatz, Jillian Kaufmann and Leah Fedoruk. These ladies provided the moral support, friendship and great dinner parties when I needed it the most.

Thank you to my co-worker, Emile deMilliano for the agronomic mentorship and moral support while I took on a career with Viterra during the final stages of finishing my thesis.

Thank you most of all to my family and friends that shared the successes and failures I experienced during my thesis. A special thanks to my parents, Ingrid and Raimund Polziehn, my sister Dr. Renee Polziehn, her husband Roger Marchand and son Thomas Marchand for their continuous love and support during the years.

This thesis was made possible by funds from the Canadian Wheat Board (CWB), University of Alberta, and Agriculture and Rural Development (ARD).

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List of Abbreviations

AC	Agriculture Canada
AAFC	Agriculture and Agri-Food Canada
ACCase	Acetyl-CoA-Carboxylase
ALS	Acetolactate Synthase
ANOVA	Analysis of Variance
°C	Celsius
C:N	Carbon:Nitrogen
E_{50}	50% Emergence
GDD	Growing Degree Days
HTT	Hydrothermal Time
IWM	Integrated Weed Management
KOH	Potassium Hydroxide
kg N ha^{-1}	Kilograms of Nitrogen per Hectare
kPA	Kilopascal
PAR	Photosynthetically Active Radiation
SMP	Seed Mortality Percent
TTC	2,3,5-triphenyltetrazolium chloride
U.S.	United States

Chapter 1. Introduction

1.1. Background

Herbicides have been used as an effective means in controlling weeds since the 1950s and are one of the most important advances in agriculture (Pike et al. 1991). In North America, herbicides can account for 20-30% of crop inputs (Derksen et al. 2002). On the Canadian Prairies, the total economic impact of weeds in barley, canola and wheat is approximately $1 billion annually (Leeson et al. 2006). Consequently, the majority of expenditures associated with managing weeds are for herbicide product and application (Leeson et al. 2006). In western Canada , fluctuating crop prices, rising input costs, occurrence of herbicide resistant weeds and public concern regarding the effects of herbicides on the environment and human health have garnered interest from scientists and growers to reduce herbicide use and rates (Beckie et al. 2008; Blackshaw et al. 2008; O'Donovan et al. 2007). The response to these concerns has led to the development and adoption of integrated weed management systems.

The concept of integrated weed management (IWM) has been used since the 1970s by weed scientists (Walker and Buchanan 1982). Although the approach to IWM has evolved over the last three decades, the principal objective is still to develop economically, ecologically and socially sustainable cropping systems that combine various agronomic practices to improve crop competition, decrease weed emergence and reduce herbicide reliance. IWM is also a component of integrated crop management systems that aims to promote crop and soil health. As a result, combining agronomic practices that produce healthy, competitive crops are essential to developing successful IWM systems.

Integrated weed management systems employ various cultural and herbicide management strategies to manage weed populations. For instance, a variety of agronomic practices that can be combined with economic thresholds and judicious herbicide use, include direct seeding, crop rotations, higher seeding rates, early seeding dates, competitive crops and cultivars and strategic fertilizer placement. Combining agronomic practices has been effective in reducing the impact of weed competition as well as delaying the development and spread of herbicide resistant weeds (Beckie and Kirkland 2003; Beckie et al. 2008). IWM is built upon a systems approach that incorporates knowledge of weed biology and weed ecology. Integrating bioecological information with agronomic practices can provide seasonal and multi-year weed control, influencing weed growth at all stages of its lifecycle (Blackshaw et al. 2008). Long term changes in weed populations can result in reduced weed emergence, weed densities, weed-crop competition, weed seed production and weed seed bank densities (Blackshaw et al. 2008; Buhler 2002; Murphy et al. 2006).

Weed seed banks are dynamic, with a number of biological processes influencing the amount of seeds being added, removed or retained in the soil seed bank. Although the temporal and spatial variability in size, composition and seed depth enhances the difficulty in studying weed seed banks (Benvenuti 2007), they are often good indicators of how successful past and present weed management strategies have been in influencing weed populations. One of the primary reasons for studying weed seed banks is to develop IWM strategies that can reduce seed bank additions, increase seed bank losses or reduce the length of time seeds are retained in the seed bank (Swanton and Booth 2004). A secondary reason for studying weed seed banks is to understand the timing and amount of weed seedling emergence. The ability to predict the magnitude and timing of weed seedling emergence is dependent on the level of dormancy expressed among seeds in a seed bank (Allen et al. 2007; Batlla and Benech-Arnold 2007; Benech-Arnold et al. 2000; Forcella et al. 2000). Knowledge of factors that affect seedling emergence can improve the implementation and effectiveness of IWM practices (Grundy 2003).

The development of IWM systems in western Canadian cropping systems have centered on the management of wild oat (*Avena fatua* L.). Despite a variety of individual herbicide and cultural management techniques available to manage wild oats, identifying optimal combinations of agronomic practices to maximize management and profitability and limit the development or spread of herbicide resistance remains at its infancy within western Canada. Improving implementation of IWM strategies requires a better understanding of wild oat population dynamics over the course of multi-year strategies. One aspect of understanding wild oat populations is to study the role of inputs and losses from the wild oat seed bank. Finding opportunities to manipulate weed seed banks through IWM strategies may also have implications on wild oat seed germination, dormancy and seed mortality. Few studies have measured the cumulative effects of IWM strategies on wild oat seed banks and wild oat seedling emergence.

The primary focus of this project was to evaluate the cumulative effects of five and six years of IWM practices, that included the use of short and tall barley cultivars, normal and high barley seeding rates and continuous and diverse crop rotations in combination with quarter, half or full herbicide rates, on wild oat seed bank density, seed mortality, seedling emergence and seedling survivorship. The following questions were addressed:

1. What are the cumulative effects of combining agronomic practices with herbicides on wild oat seed bank density and seed mortality?
2. Can wild oat seed bank density predict wild oat emergence?
3. Can wild oat seed production, emergence and biomass estimate the wild oat seed bank?
4. How many growing degree days (GDD) are required for 50% wild oat emergence in central Alberta?
5. What are the cumulative effects of combining agronomic practices with herbicides on wild oat seedling emergence and seedling survivorship prior to and subsequent to herbicide application?

The experimental hypotheses of this research were that the cumulative effects of five and six years of optimal IWM practices will reduce wild oat seed bank densities, seedling emergence and seedling survivorship and enhance seed mortality. In addition, a close relationship will exist between the wild oat seedling emergence and seed bank density. Similarily, wild oat seed banks can be estimated using information on wild oat seed inputs, seasonal emergence and biomass. This research project will provide valuable information on wild oat seed bank dynamics to scientists, agronomists and farmers for implementing and developing integrated approaches to managing wild oats.

1.2. Literature Cited

Allen P. S., R. Benech-Arnold, D. Batlla, and K. J. Bradford. 2007. Modeling of seed dormancy. Pages 73-112 *In* K. J. Bradford and H. Nonogaki, eds. Seed Development, Dormancy and Germination. Ames, Iowa: Blackwell Publishing Limited.

Batlla, D. and R. L. Benech-Arnold. 2007. Predicting changes in dormancy level in weed seed soil banks: Implications for weed management. Crop Protect. 26:189-197.

Beckie, H. J. and K. J. Kirkland. 2003. Implication of reduced herbicide rates on resistance enrichment in wild oat (*Avena fatua*). Weed Technol. 17:138-148.

Beckie, H. J., J. Y. Leeson, G. Thomas, L. M. Hall, and C. A. Brenzil. 2008. Risk assessment of weed resistance in the Canadian Prairies. Weed Technol. 22:741-746.

Benech-Arnold, R. L., R. A. Sanchez, F. Forcella, B. C. Kruk, and C. M. Ghersa. 2000. Environmental control of dormancy in weed seed banks in soil. Field Crops Res. 67:105-122.

Benvenuti, S. 2007. Natural weed seed burial: Effect of soil texture, rain and seed characteristics. Seed Sci. Res. 17:211-219.

Blackshaw, R. E., K. N. Harker, J. T. O'Donovan, H. J. Beckie, and E. G. Smith. 2008. Ongoing development of integrated weed management systems on the Canadian Prairies. Weed Sci. 56:146-150.

Buhler, D. D. 2002. Challenges and opportunities for integrated weed management. Weed Sci. 50:273-280.

Derksen, D. A., R. L. Anderson, R. E. Blackshaw, and B. Maxwell. 2002. Weed dynamics and management strategies for cropping systems in the Northern Great Plains. Agron. J. 94:174-185.

Forcella, F., R. L. Benech Arnold, R. Sanchez, and C. M. Ghersa. 2000. Modeling seedling emergence. Field Crops Res. 67:123-139.

Grundy, A. C. 2003. Predicting weed emergence: A review of approaches and future challenges. Weed Res. 43:1-11.

Leeson J. Y., A. G. Thomas, and J. T. O'Donovan. 2006. Economic impact of alien weeds on wheat, barley and canola production. Proc. Canadian Weed Sci. Soc., Nov. 27-29. Victoria, BC .

Murphy, S. D., D. R. Clements, S. Belaoussoff, P. G. Kevan, and C. J. Swanton. 2006. Promotion of weed species diversity and reduction of weed seedbanks with conservation tillage and crop rotation. Weed Sci. 54:69-77.

O'Donovan, J. T., R. E. Blackshaw, K. N. Harker, G. W. Clayton, J. R. Moyer, L. M. Dosdall, D. C. Maurice, and T. K. Turkington. 2007. Integrated approaches to managing weeds in spring-sown crops in western Canada . Crop Protect. 26:390-398.

Pike, D. R., M. D. McGlamery, and E. L. Knake. 1991. A case study of herbicide use. Weed Technol. 5:639-646.

Swanton, C. J. and B. D. Booth. 2004. Management of weed seedbanks in the context of populations and communities. Weed Technol. 18:1496-1502.

Walker, R. H. and G. A. Buchanan. 1982. Crop manipulation in integrated weed management systems. Weed Sci. 30:17-24.

Chapter 2. Literature Review

2.1. Integrated Weed Management

Sustainable integrated weed management (IWM) systems are built from a variety of management strategies that enhance crop diversity and reduce the stability of weed communities. Implementing concepts of weed biology and ecology into IWM provides a holistic approach to managing cropping systems. Developing a comprehensive IWM system uses agronomic strategies such as diverse crop rotations, higher seeding rates, strategically placed fertilizer, early weed removal and competitive crops and cultivars to manipulate weed survival, growth and reproduction. Many agronomic practices are effective on their own in reducing weed populations and enhancing crop yields but in combination they can have further long term management benefits (Anderson 2003). Furthermore, integrating agronomic practices may reduce the reliance on herbicides, especially if used with economic thresholds and crop scouting.

Current research is identifying cropping systems that integrate agronomic practices to manage weeds under diverse cropping systems across all agro-ecological regions in Western Canada. Additional research is needed to develop systems that growers perceive as economically viable and where the risk of adoption is perceived as low. Despite the development of IWM systems, growers will still need to select agronomic practices that complement existing crop production systems as well as fit the economic, social and environmental standards of their operation. Consequently, no single IWM strategy will be appropriate for all growers; therefore, the optimal combination of agronomic practices will depend on the agro-ecological region, farm machinery, crop choice, economics and grower attitudes and beliefs.The current section will outline the most common agronomic practices utilized in western Canada that can be adopted into IWM systems.

2.1.1. Components of Integrated Weed Management in Western Canada

2.1.1.1. Direct Seeding

Direct seeding has increased in adoption across the Canadian Prairies since the early 1990s. In Alberta, direct seeding increased from 3% of the total area in 1991 to 48% in 2006 (Statistics Canada 2008). Direct seeding has led to an overall improvement in soil quality and moisture conservation by reducing soil erosion (Mostaghimi et al. 1992; Tessier et al. 1990), minimizing evaporative water losses (Cutforth and McConkey 1997; Cutforth et al. 2002; Cutforth et al. 2006), improving water infiltration (Arshad et al. 1999; Azooz and Arshad 1996; Azooz and Arshad 1998), and increasing soil organic matter (Campbell et al. 1989; Campbell et al. 1998). Furthermore, managing diversified cropping systems under direct seeded (minimum and zero-tillage) systems can enhance and stabilize net farm incomes (Zentner et al. 1992; Zentner et al. 2002a; Zentner et al. 2002b).

Although direct seeding continues to gain popularity, some expected consequences can include lower spring soil temperatures that reduce or delay crop seedling emergence (Lafond et al. 1996), increased surface residues that immobilize nitrogen (Schoenau and Campbell 1996) and additional costs and equipment modifications of ground openers, straw choppers and spreaders to manage heavy crop residues (Canola Council of Canada 2003). The adoption of direct seeding has also led to changes in herbicide use (Zentner et al. 2002a; Zentner et al. 2002b), including a high frequency of pre-seed, pre-harvest and post-harvest gylphosate applications. A pre-seed application that includes glyphosate has become a key practice in managing early emerging weeds and optimizing crop productivity (Johnson et al. 2002). Weed communities have shifted under direct seeded systems, responding with a decrease in annual weed densities but an increase in winter annuals, biennials and perennials (Blackshaw et al. 2006; Derksen et al. 2002; Thomas et al. 2004). Although glyphosate efficacy depends on the weed species and time of weed emergence (Johnson et al. 2002), it has been effective in managing various perennial weeds such as quackgrass [*Elymus repens* (L.) Gould] (Harker and Vanden Born 1997) and foxtail barley (*Hordeum jubatum* L.) (Blackshaw et al. 1999). Despite shifts in the weed community, lower weed densities have been reported by growers following 5 to 10 years of direct seeding (Blackshaw et al. 2008).

Direct seeded systems can create an opportunity to exploit weed seed banks. Seeds that remain on the soil surface tend to be at greater risk for mortality (Blackshaw et al. 2008), since seeds are exposed to environmental extremes and seed predation (Cromar et al. 1999; Egley 1986; Froud-Williams et al. 1984). Unlike conventional tillage, there is less spring soil disturbance in direct seeding which reduces the number of weed seeds stimulated to germinate and be depleted from the soil seed bank. However, seeds of common lambsquarters

(*Chenopodium album* L.), stinkweed (*Thlaspi arvense* L.), green foxtail [*Setaria virdis* (L.) Beauv.], wild buckwheat (*Polygonum convolvulus* L.) and wild oat (*Avena fatua* L.) that remain near the soil surface in direct seeded fields emerge earlier and more uniformly, improving the opportunity for early herbicide applications (Bullied et al. 2003). Overall, direct seeding has played an integral part in IWM and its successful adoption may be attributed to its use with other weed management strategies, such as using diverse crop rotations and competitive crops and cultivars (Derksen et al. 2002).

2.1.1.2. Crop Rotation

In western Canada, a diverse number of cereal, oilseed, pulse and forage crops and cultivars are grown as part of an integrated approach to weed management. The sequence of crops grown in a cropping system varies across soil zones. For example, the cropping sequence in the Black soil zone typically consists of a cereal-oilseed-cereal-pulse rotation. Canola (*Brassica napus* L.) and peas (*Pisum sativum* L.) are the most common oilseed and pulse crops, respectively, grown following a cereal crop such as wheat (*Triticum aestivum* L.) or barley (*Hordeum vulgare* L.). In western Canada, the majority of canola grown is herbicide tolerant, either to glufosinate or glyphosate (Beckie et al. 2006). Furthermore, despite wheat being the most commonly grown cereal, oats (*Avena sativa* L.) and barley have displaced some wheat acres in the last 25 years. Conversely, in the Brown soil zone, the traditional cropping sequence has been summerfallow-wheat; however, current rotations are now introducing pulses such as lentils (*Lens culinaris*. Medikus), field peas and chickpeas (*Cicer arietinum* L.) to diversify nutrient and water usage. Beyond weed management, diversifying crop rotations can also reduce financial risk, decrease disease incidence, improve soil quality and increase nutrient and moisture reserves (Zentner et al. 2002b). Despite higher production costs, the economic benefit of including an oilseed and pulse crop in rotation with cereals is a higher and stable farm net income (Zentner et al. 2002b). Consequently, increased crop diversity is essential to attaining higher productivity and economic return on the Canadian Prairies.

Crop rotations can disrupt the life cycle and growth habit of weeds through variations in crop life cycles, cultivars and seeding and harvesting dates (Anderson 2003; Anderson 2004; Anderson 2005; Derksen et al. 2002; Liebman and Dyck 1993). Typically, cropping systems include a rotation of grass and broadleaf crops, since grass weeds may become more predominant in grass crops and broadleaf weeds more common among broadleaf crops. Balanced crop rotations also include using competitive and non-competitive crops to minimize weed interference; therefore, rotations should not include growing non-competitive crops, such as flax (*Linum usitatissimum* L.), lentils or chickpeas in succession. Crop rotations that alter the time of seeding and herbicide application can change selection pressures on early versus late emerging weeds. Blackshaw (1994) reported increased suppression of downy brome (*Bromus tectorum* L.) populations when fallow or spring seeded canola was included in a winter wheat (*Triticum aestivum* L.) rotation compared to a continuous winter wheat rotation. Diversity in a crop rotation can also provide variation in herbicide application timing and modes of action, curtailing the selection of herbicide resistant weeds (Anderson 2003).

While crop rotations produce measurable changes in the abundance and composition of weed communities, the effects are difficult to separate from other management practices, such as tillage (Legere and Stevenson 2002) and herbicide usage. Crop rotations under reduced tillage have been reported to reduce fecundity of both grass and broadleaf weed species (Kegode et al. 1999). Murphy et al. (2006) found that using three crops in rotation [corn (*Zea mays* L.) - soybean [*Glycine max* (L.) Merr]-winter wheat], seed bank densities in a direct seeded field can be reduced as much as 80% over six years. As a result, crop rotation is an integral component in reducing weed populations, especially when used in combination with other agronomic practices.

2.1.1.3. Competitive Crops and Cultivars

In western Canada, spring barley is still considered the most competitive spring-sown crop species when compared to canola (Dew and Keys 1976), spring wheat and flax (Dew 1972). Although it is recognized that crops vary in their ability to compete with weeds, also important are the differences in competitive abilities among cultivars within a crop species. Differentiating the competitive ability of cultivars is typically based on their ability to (i) tolerate weed competition without compromising grain yield and (ii) suppress weed growth (Goldberg and Landa 1991; Jordan 1993). Several plant characteristics have been attributed to competitiveness, including plant height, early maturity, crop establishment, tillering, structure of crop canopy, interception of photosynthetically active radiation (PAR), early biomass accumulation, flag leaf length, ground cover, and timing of spike emergence (Beckie et al. 2008b; Champion et al. 1998; Hucl 1998; Huel and Hucl 1996; Korres and Froud-Williams 2002; Lemerle et al. 1996; Mason et al. 2007; O'Donovan et al. 2005b; Wicks et al. 1986). In western Canada, barley varieties have been shown to differ in their ability to compete with weeds. Semi-dwarf and hull-less varieties are less competitive with wild oat or tame oat than taller hulled barley varieties (O'Donovan et al. 2000; Watson et al. 2006) and typically suffer greater yield losses (O'Donovan et al. 2000). Since the hull is typically removed during harvest, the embryo of hull-less varieties are susceptible to mechanical injury and fungal attack (White et al. 1999); thus, reduced seed viability, germination and seedling emergence can occur, reducing a plants ability to successfully compete with weeds (O'Donovan et al. 2000). Hull-less barley varieties may also experience poor seedling emergence due to shorter coleoptiles or coleoptiles growing abnormally as a result of a damaged embryo (Box et al. 1999). Alternatively, Watson et al. (2006) suggest that comparing the competitive abilities of semi-dwarf to tall varieties and hull-less to hulled varieties may be complicated by pleiotropic effects of *sdw* (semidwarf) and *n* (naked caryopsis) genes, respectively.

Research is underway to measure the competitive ability of hybrid canola varieties. Canola hybrids have been found to be more competitive than open pollinated varieties (Hanson et al. 2008; Harker et al. 2003a; Zand and Beckie

2002). Hybrid cultivars benefit from rapid emergence and early canopy closure minimizing competition from weeds and maximizing yield (Harker et al. 2003a). Generally, growing competitive cultivars of barley, wheat, canola and field pea is an important IWM strategy to enhance crop competitiveness (Beckie et al. 2008b; Harker et al. 2008a; Hucl 1998; O'Donovan et al. 2005b; Watson et al. 2006).

2.1.1.4. Seeding Date

Subjecting weeds to temporal diversity by alternating planting and harvesting dates can also improve weed management. The benefits of early seeding have been recognized and are commonly used in cropping systems across western Canada. Early seeded crops optimize utilization of spring soil moisture (Angadi et al. 2004), minimize the risk of heat stress during flowering (Kirkland and Johnson 2000), out-compete weeds that require warmer soil temperatures for germination (Blackshaw et al. 2005b; Harker et al. 2005), reduce the opportunity for disease and insect problems during peak infection or infestation periods (Krupinsky et al. 2002; Olfert and Weiss 2002), enhance yields (Chen et al. 2005; Clayton et al. 2004; Kirkland and Johnson 2000) and encourage earlier harvest dates. Delayed seeding within western Canada is not favourable due to the short growing season. Furthermore, later seeding dates can result in yield reductions in wheat (Briggs and Aytenfisu 1979), barley (Juskiw and Helm 2003), canola (Degenhardt and Kondra 1981), flax (Thompson et al. 1988), oats (May et al. 2004) and field peas (Ali-Khan 1977).

Early seeding dates promote early crop emergence, maximizing crop yields and economic returns. Coupling early crop emergence with early weed removal can maximize weed control and crop yield. Early weed control in canola can increase yield, minimize dockage, reduce weed biomass and promote higher net revenues (Clayton et al. 2002; Harker et al. 2004; Harker et al. 2008b; O'Donovan et al. 2006b). Early crop emergence and rapid growth following an in-crop herbicide application can provide sufficient crop competition for later emerging weeds. Consequently, in glyphosate-resistant canola systems O'Donovan et al. (2006b) found no advantage with respects to yield, dockage or weed biomass, for applying two in-crop glyphosate applications in the current cropping season to manage late emerging weeds. Furthermore, shallow seeding depths can promote early crop emergence (Gan et al. 1992), which can allow a crop to utilize early season moisture and nutrients before weeds emerge.

Temporal diversity can also include using fall seeded crops, such as winter wheat, winter rye (*Secale cereal*e L.) or winter triticale Triticale (X *Triticosecale* Wittmack). For example, early emerging annual weeds are typically outcompeted by winter wheat in the spring due to the formation of a dense canopy (Anderson 2008). As a result, winter wheat grown in a diverse rotation can minimize summer annual weeds from adapting and establishing (Blackshaw 1994; Schreiber 1992). Although the use of winter and perennial crops in rotation are important in managing weeds, a detailed discussion of their role is beyond the scope of this review.

2.1.1.5. Higher Crop Seeding Rates

In addition to selecting the most competitive crop cultivar, increasing crop seeding rate can also improve the competitiveness of the crop. Recommended seeding rates have been determined in western Canada for a variety crops, but usually under weed-free conditions (O'Donovan et al. 2007a). Seeding rates do not always represent the number of seedlings emerged in the field, even when germination rates exceed 90%; as a result, the percent germination of a seed lot can overestimate the number of seedlings that emerge under field conditions (Harker et al. 2003a). Harker et al. (2003a) reported canola emergence of hybrid and open pollinated canola to be half of the seeds planted; therefore, a seeding rate of 100 to 200 seeds m^{-2} resulted in 46 to 90 open pollinated Exceed plants m^{-2} and 54 to 102 hybrid InVigor 2153 plants m^{-2}.

Nevertheless, higher crop seeding rates of barley (O'Donovan et al. 1999b; O'Donovan et al. 2000; O'Donovan et al. 2001), wheat (Blackshaw et al. 2000; O'Donovan et al. 2006a; Xue and Stougaard 2002), peas (Johnston et al. 2002) and canola (Hanson et al. 2008; Harker et al. 2003a) can reduce weed biomass and increase crop yield. For example, wild oat biomass can be reduced by using higher barley seeding rates (i.e. 125 to 175 kg ha^{-1}) to achieve crop densities between 200 and 250 plants m^{-2} (O'Donovan et al. 1999b; O'Donovan et al. 2000; O'Donovan et al. 2001). Increasing barley densities from 150 to 250 plants m^{-2} under wild oat densities of 50 plants m^{-2} minimized yield loss from 20 to 14% (O'Donovan et al. 1999b). Combining a competitive hybrid canola cultivar with a high seeding rate and early weed removal can be used to increase canola yield and improve weed management (Harker et al. 2003a). However, growers may be more reluctant to increase canola seeding rates compared to barley or wheat due to the high seed costs associated with herbicide resistant canola varieties (O'Donovan et al. 2004). Furthermore, higher seeding rates may not be a viable management option in all agroecosytems across the Canadian Prairies. In semiarid regions, higher seeding rates may compromise crop quality. Increasing malt barley seeding rates under rain-fed conditions (<300mm) compared to irrigated conditions (>300mm) provided only modest increases in yield but reduced the proportion of plump kernels (McKenzie et al. 2005). However, higher seeding rates have become a highly effective and viable option for weed suppression in organic production systems. Mason et al. (2007) indicated that doubling wheat seeding rates from 300 seeds m^{-2} to 600 seeds m^{-2} improved both wheat yield and weed suppression; furthermore, the benefits of a doubled wheat seeding rate were not cultivar specific.

Enhancing crop seeding rates can also improve the efficacy of herbicides applied at reduced rates. O'Donovan et al. (2006a) reported wild oat herbicides to be more successful in reducing wild oat shoot biomass and seed in the soil seed bank when wheat seeding rate was increased from 75 kg ha^{-1} (100 plants m^{-2}) to 150 kg ha^{-1}(200 plants m^{-2}). In barley, applying tralkoxydim at 50 or 100% of the recommended rate in combination with higher barley seeding rates reduced wild oat fecundity as well as the amount of wild oat seed in the soil seed bank (O'Donovan et al. 2001). Combining higher seeding rates with reduced herbicide rates to limit weed seed return is also an effective strategy to delay or prevent the selection of resistant wild oat biotypes (Beckie and Kirkland 2003; O'Donovan et al. 2001). In addition to weed suppression and improved herbicide performance, higher seeding rates can reduce dockage (Harker et al. 2003a) and branching in canola (Hanson et al. 2008), improve crop uniformity, shorten crop maturity and reduce the risk of urea-induced injury from seed placed nitrogen (O'Donovan et al. 2008).

2.1.1.6. Strategic Fertilizer Placement

Many weed species capitalize on high soil fertility, reducing the amount of nutrients available for crop growth. Large quantities of soil nutrients, including nitrogen, phosphorous, potassium, calcium and magnesium can be utilized by weeds (Vengris et al. 1953). On the Canadian Prairies, weeds can respond to added concentrations of nitrogen and phosphorous with increased shoot and root growth which frequently exceeded shoot and root growth of wheat and canola (Blackshaw et al. 2003; Blackshaw et al. 2004a). Consequently, understanding weed responses to fertility can improve fertilizer management strategies. As a result, optimizing fertilizer application timing and placement as well as using slow release fertilizers has become an important practice to optimize crop yield and quality as well as reduce weed interference (Di Tomaso 1995; Malhi et al. 2001; Malhi et al. 2003).

Spring fertilizer applications in spring wheat, barley, canola and peas, have typically optimized crop yield and reduced weed biomass (Blackshaw et al.

2004b; Blackshaw et al. 2005a; Blackshaw et al. 2005b). The competitive ability of many weed species is also influenced by the placement of fertilizer (Blackshaw et al. 2002b; Blackshaw and Molnar 2009). Blackshaw et al. (2004b) quantified the effects of nitrogen fertilizer timing and placement on the management of wild oat, green foxtail, wild mustard [*Brassica kaber* (DC.) L.C. Wheeler var. pinnatifida (Stokes) L.C. Wheeler] and common lambsquarters in spring wheat. The density and shoot biomass of weeds were generally higher under fall applied nitrogen treatments. Furthermore, greater weed density and shoot biomass occurred when nitrogen was surface broadcasted rather than sub-surface banded or point injected. A simultaneous increase in spring wheat yield also occurred when nitrogen was sub-surface banded or point injected. After four consecutive years of fertilizer application, the weed seed bank was reduced by 25 to 63% with a point injected N compared with surface broadcasted N. O'Donovan et al. (2008) also compared five rates (0, 30, 60, 90 and 120 kg ha^{-1}) of seed placed and side banded urea at three barley seeding rates (200, 300 and 400 seeds m^{-2}). High rates (>60 kg ha^{-1}) of seed placed N increased the risk of urea-induced seedling damage, causing a reduction in barley plant densities. Reduced barley densities not only contributed to earlier wild oat competition and fecundity but delayed barley maturity. However, as rates of side banded nitrogen increased, barley yields improved and the time to maturity and wild oat fecundity decreased. Higher barley seeding rates under all nitrogen placements and rates did not increase yields; however, they reduced wild oat fecundity and reduced the risk of urea-induced injury in seed placed N, but not as low as side banding. Recently, Blackshaw and Molnar (2009) found that mid-row banded and seed-placed phosphorous resulted in higher wheat yields under competitive weed pressure compared to surface-broadcast phosphorous applications. In addition, weed biomass and seed bank densities were also lower with seed-placed or sub-surface phosphorous applications. Overall, managing fertilizer timing and placement are suitable strategies for improving crop competitiveness within an integrated weed management strategy.

2.1.1.7. Silage, Green Manure and Cover Crops

Silage, green manure and cover crops are not only effective at increasing the diversity of a crop rotation but are effective for managing weed populations. Silage provides an opportunity to reduce weed populations by harvesting weeds prior to weed seed maturity. In western Canada, silage crops that use barley and/or corn can be an effective tool in managing weed populations. Harker et al. (2003b) reported early cut barley silage without herbicides to be as effective in reducing wild oat populations as using herbicides in barley grain production. In early harvest silage treatments at Lacombe, Alberta, wild oat plant densities declined from 40 plants m^{-2} in 1997 to less than 20 plants m^{-2} in 1999; consequently, two years of early cut barley silage can lead to significant depletions in the wild oat seed bank.

Green manure and cover crops have been typically adopted in organic production, but are occasionally being incorporated in conventional systems. Cover crops can suppress weed competition, manipulate environmental conditions that influence the germination and emergence of weeds, and release phytotoxins (Liebman and Davis 2000). In conventional cropping systems, growers are starting to adopt cover crops, such as winter rye, to provide ground cover following low residue crops, such as potatoes (*Solanum tuberosum* L.) or sugar beets (*Beta vulgaris* L.) (Blackshaw et al. 2008).

Organic growers have also adopted forage legumes such as yellow sweetclover (*Melilotus officinalis* L.) and red clover (*Trifolium pratense* L.) as green manure to suppress weed competition and enhance available nitrogen in the soil. Blackshaw et al. (2001) determined that yellow sweetclover green manure can successfully replace fallow periods in dryland cropping systems. The allelopathic compounds found in the decomposing residues have the potential to suppress an assortment of perennial [dandelion (*Taraxacum officinale* Weber in Wiggers) and perennial sowthistle (*Sonchus arvensis* L.)] and annual [stinkweed (*Thlaspi arvense* L.), kochia (*Kochia scoparia* L.), flixweed [*Descurainia sophia* (L.) Webb ex Prantl], Russian thistle (*Salsola tragus* L.) and downy brome] weeds. Similar levels of weed suppression occurred whether sweetclover was harvested as hay or its residues were incorporated or left on the soil surface. Conventional cropping systems also benefit from the addition of perennial forages such as alfalfa (*Medicago sativa* L.) or perennial grasses, since they are effective management tools for suppressing annual weeds.

Frequent cutting of perennial forages can also reduce the vigor and seed production of competitive weeds (Lafond et al. 1996). In a survey of 117 fields in

Manitoba, weed populations in cereal fields that were preceded with alfalfa or cereal grain crop were compared (Ominski et al. 1999). Cereal fields following alfalfa contained lower populations of wild oat, Canada thistle [*Cirsium arvense* (L.) Scop.], wild mustard and cleavers (*Galium aparine* L.) than in continuous cereal crops.

2.1.1.8. Economic Thresholds

An informed spray decision begins with an assessment of weed populations through field scouting to determine whether herbicides are necessary. An economic threshold, defined as the density of weeds at which the cost of the herbicide and application is equal to the value of the crop lost to weed competition, have been recommended by several researchers (Buhler et al. 1997b; Cousens et al. 1986; Doyle et al. 1986; Forcella et al. 1996; Gerowitt and Heitefuss 1990; Hamman 1979; Jones and Medd 2000; Monks et al. 1995; O'Donovan et al. 2005a; Wilkerson et al. 1991). Judicious application of herbicides can improve net returns by reducing the number of herbicide applications, minimizing the risk of developing herbicide resistance and reducing the herbicide footprint in the environment (O'Donovan 1996; O'Donovan et al. 2005a). An economic threshold can be an important strategy for making spray decisions, but is difficult to implement for weed management (Cousens et al. 1987; O'Donovan 1996). Current decision models fail to capture the random, patchy spatial distribution of weeds (Wiles et al. 1993) and few models capture crop yield loss between various weed-crop combinations or from a mixed population of weed species. Furthermore, the implications of weed seeds produced by escapes on future infestations and weed seed bank build-up are not readily incorporated into decision making frameworks.

In western Canada, a decision making framework is available to assist growers with herbicide applications for wild oat. Regression models were first established in the 1970s to determine the amount of crop yield loss from wild oat competition (Dew 1972; Dew and Keys 1976), but additional information on crop density and time of weed and crop emergence have been included in these models (Cousens et al. 1987; O'Donovan et al. 1999b). O'Donovan et al. (2005a) broadened the regression model for estimating yield loss and loss revenue to include wild oat and volunteer cereals. In this case, the economic threshold concept was more highly utilized for low value crops, such as feed barley or wheat than in high value crops, like canola and hard red spring wheat. In high value crops growers are unlikely to exclude an in-crop herbicide application regardless of weed population. The current adoption of current economic thresholds may be limited by the simplicity and accuracy of these models (Wilkerson et al. 2002); however, economic thresholds have an important role in an integrated crop management system, whether as a predictive or educational tool to promote informative weed management decisions.

2.1.2. Combining Agronomic Practices into an IWM System

Although adopting one or two weed management strategies can be effective in reducing weed competition, greater success can be achieved in systems that incorporate several management tactics. A successful integrated weed management approach has been developed for foxtail barley in direct seeded systems. Blackshaw et al. (1999) reported reductions in foxtail barley biomass and seed production in a multi-year approach that combined pre-seed and post-harvest glyphosate applications with a diverse crop rotation, higher crop seeding rates and banded nitrogen. Pre-seed applications of glyphosate provided early weed control to enhance crop competitiveness and optimize yield. An additional application of glyphosate during post-harvest effectively managed older cohorts of foxtail barley. Diversifying the rotation with a broadleaf crop like flax also allowed the use of selective grass herbicides, quizalofop and sethoxydim, which controlled foxtail barley seedlings and suppressed established adult plants. Increasing wheat seeding rate from 75 kg ha^{-1} to 115 kg ha^{-1} reduced foxtail barley biomass and seed production as much as 50%; however, increasing flax seeding rate did not have an impact on foxtail barley biomass and seed production.

Integrating agronomic practices and knowledge has also improved weed management in canola production. Harker et al. (2003a) conducted field experiments in Alberta to determine the effects of combining glufosinate-tolerant canola cultivar (hybrid or open-pollinated), crop seeding rate (100, 150, or 200 seeds m^{-2}) and time of weed removal (two-, four-, or six-leaf stage of canola) on canola yield and weed biomass. A 41% increase in yield occurred when combining a higher seeding rate and early weed removal with a hybrid canola variety compared to using a low seeding rate and late weed removal with an open pollinated cultivar. Higher seeding rates and early weed removal provided the most effective management system to reduce weed biomass in both hybrid and open-pollinated crops. However, higher seedling emergence and seed yield were achieved using higher seeding rates and early weed removal with a competitive hybrid compared to an open pollinated cultivar. Similarly, using higher seeding rates with a competitive hybrid cultivar also contributed to the lowest levels of dockage. Overall, combining optimal agronomic practices in canola production can help increase farm revenue as well as provide an effective system of integrated weed management.

Previous IWM research studies have focused on the effects of one or two agronomic factors; however, current research is now addressing the effects of combining several agronomic practices with herbicides under different cropping systems. Simultaneous four year field studies were conducted within a direct seeded barley-field pea–barley-field pea rotation and spring wheat–canola–spring wheat–canola rotation to identify the impact of integrating agronomic practices with herbicides for sustainable weed management (Blackshaw et al. 2005a; Blackshaw et al. 2005b). Combining early seeding, higher crop seeding rates, and spring-applied fertilizer resulted in the most competitive cropping systems. In the spring wheat–canola–spring wheat–canola rotation, increasing the crop seeding rate by 1.5 times reduced the weed seed bank 31 and 44 % at two locations (Lethbridge, AB and Scott, SK, respectively). Similarly, reductions in the weed seed bank in the 50 and 100% herbicide rate treatments of the barley-field pea–barley-field pea rotation occurred when seeding rate was increased. Weed biomass was also reduced at the higher crop seeding rates in both rotations.

Furthermore, both rotations experienced more weed competition during the April seeding date than May seeding date; however, higher crop seeding rates during the early seeding date were more beneficial in reducing weed biomass. Similar crop yield and weed biomass were achieved when higher seeding rates were combined with a 50% or 100% herbicide dose. Similarly, spring applications of nitrogen versus fall applications also lowered weed biomass, and in some cases reduced the weed seed bank and increased crop yield. Competitive cropping systems that use a variety of agronomic practices can effectively increase crop yield, reduce weed biomass and seed banks, even when herbicide rates were reduced. Consequently, a competitive cropping system provides growers an opportunity to reduce herbicide rates or the number of herbicide applications, improving the economic and environmental sustainability of their operation.

2.2. Weed Seed Banks

The soil seed bank contains a reservoir of viable weed seeds buried in or on the soil surface (Cavers 1995; Simpson et al. 1989). The age structure of seeds in the seed bank is complex, containing a composite of cohorts of various ages and viability (Templeton and Levin 1979). Seed burial studies have demonstrated seed longevity, showing that many weed species can persist in soil for decades (Telewski and Zeevaart 2002; Toole and Brown 1946). Thompson and Grime (1979) further distinguished seed banks as either transient or persistent. Transient seed banks are composed of seeds that typically germinate or die within one year of dispersal, such as dandelion, common groundsel and kochia (Figueroa et al.

2007; Hacault and Van Acker 2006; Schwinghamer and Van Acker 2008), whereas persistent seed banks contain seeds that remain viable for more than one year, such as wild oat and lambsquarters (Banting 1962; Forcella et al. 1992).

The persistence of a seed bank is influenced by soil disturbance (Thompson et al. 1998), seed burial (Bekker et al. 1998; Thompson et al. 1998), dormancy (Benech-Arnold et al. 2000) and protective seed coats (Chee-Sanford et al. 2006; Harrison et al. 2003; Kremer 1993; Kremer 1986; Thompson 1987). Physical and chemical attributes of the seed are important in maintaining longevity and structural integrity. For example, weed species with thick seed coats such as velvetleaf (*Abutilon theophrasti* Medicus) and lamb's quarter are likely to form persistent seed banks; conversely, seeds of weed species that form transient seed banks such as kochia rely on chemical defenses, including *ortho*-dihydroxyphenols (Davis et al. 2008). Small, compact seeds are more likely to persist than large, flattened or elongated seeds (Thompson et al. 1993); however, seed size interacts with other factors including seed burial and dormancy to influence persistence (Bekker et al. 1998; Thompson et al. 1998). In addition, seed persistence is a gradient of habitat stability. Seeds in stable habitats, including woodlands and pastures have decreased seed persistence whereas cropping systems characterized by high disturbance are prone to host seeds with increased seed persistence (Thompson et al. 1998). In many natural habitats, seed persistence is a function of seed burial depth and seed morphology, including seed size and shape (Ghersa and Martinez-Ghersa 2000; Thompson et al. 1998; Venable and Brown 1988). In cropping systems, cultural practices such as tillage have confounded the relationship between seed size and disturbance, because large seeds buried through tillage can have increased persistence (Thompson et al. 1998). The adoption of zero tillage may restore the link between seed size and burial depth, whereby large weed seeds near the soil surface become less persistent. Nevertheless, selection for physiological traits consistent with seed bank persistence may be experienced by weed species adapted to cropping systems by life history, herbicide resistance, phenology and other plant traits (Ghersa and Martinez-Ghersa 2000; Thompson et al. 1998).

Soil seed banks not only reflect cropping history but indicate long term success of agronomic practices on controlling weed growth and minimizing seed inputs (Roberts 1981). In agricultural systems, seed bank densities can range from zero to one million seeds per square meter (Fenner 1985). However, the density and composition of weed species in the seed bank differs among agricultural systems due to differences in weed management and environmental conditions (Cardina et al. 2002; Clements et al. 1996; Davis et al. 2005; Murphy et al. 2006; Sosnoskie et al. 2006; Swanton et al. 2006). In a 6 year study conducted by Murphy et al. (2006) in Ontario, seed bank densities were reduced from 41, 000 seeds m^{-2} to 8,000 seeds m^{-2} when a diverse crop rotation of corn-soybean-winter wheat under no-till was adopted. Furthermore, weed diversity also increased under this management system, shifting from predominantly annual weed species to winter annuals, biennials, and perennials.

The role of weed seed banks in the evolutionary and genetic dynamics of weed populations has not been carefully examined. Seed banks have been described as a "genetic or evolutionary memory", outlining the genetic history of a plant population (Templeton and Levin 1979). Seed genotypes that accumulate in the soil seed bank over many growing seasons may be a source of genetic variation for weed populations (Levin 1990); therefore, seed banks can buffer against selective pressures by re-introducing seed genotypes that were successful in the past (Templeton and Levin 1979). Furthermore, seed populations of annual species that exhibit dormancy cycling may buffer genetic loss and genetic bottlenecks that result from severe population fluctuations (Cohen 1966; Nunney 2002). Genetic novelty may also be introduced in a plant population through the occurrence of mutations that develop in aging dormant seeds (Levin 1990). Although some studies concur that the soil seed bank is a source of genetic variation to above ground plant populations (Cabin 1996; Cabin et al. 1998; Castillo 1994; Liu et al. 2006; Morris et al. 2002; Tonsor et al. 1993), selection pressures may have a greater influence in the genetic variability of a plant population (Brainard et al. 2007; Honnay et al. 2008; Mahy et al. 1999; Mandák et al. 2006; Vitalis et al. 2004).

In arable fields experiencing environmental stochasticity, transient and persistent weed seed banks are an important component in the restoration of aboveground populations. The weed seed bank is dynamic, with a number of natural processes influencing the number of seeds entering, leaving or persisting in the seed bank (Figure 2.1.). Since each of these processes is influenced by management practices, the focus of this section is to describe the natural processes involved in regulating the seed bank and how management practices influence these processes to minimize the weed seed bank.

2.2.1. Seed Entry

Weed seeds can enter the seed bank through a number of external sources, including the movement of equipment, contaminated crop seed, invertebrates and vertebrates, wind or manure (Buhler et al. 1997a). Typically, the amount of seed entering through these sources may be minor, but can be an important source in establishing new weed infestations. For example, a study of 20 New York farms reported an average of 340 weed seeds m^{-2} added to the soil seed bank from manure, with the highest amount from the study recorded as 1900 seeds m^{-2} (Mt Pleasant and Schlather 1994). Consequently, seed banks with low seed densities would be largely influenced by the addition of manure containing a large proportion of weed seeds; however, application of manure with low weed seed densities may have less impact on weed populations emerging from seed banks that already contain a large proportion of seeds. The introduction of new weed species can occur with the application of manure, especially if livestock have been provided feed grown outside the local area. The introduction of velvetleaf onto New York farms in the 1970s is believed to be a consequence of spreading manure from cows fed corn imported from the Midwest U.S. (Mt Pleasant and Schlather 1994).

Harvest losses can contribute to significant additions of volunteer crop and weed seeds in the seed bank. In canola, approximately 6% of harvested seed enters the seed bank, which is approximately 20 times the normal canola seeding rate of 4 to 5 kg ha^{-1} or 3,000 seeds m^{-2} (Gulden et al. 2003a). Alternatively, seed losses in cereals are not as extreme, whereby losses from shattering and harvesting wheat range between 35 and 800 seeds m^{-2} (Clarke 1985). Weed seeds are also ejected from combine harvesters with chaff, which can extend the patchy distribution of weed populations (Shirtliffe and Entz 2005).

Seed rain is the primary source for replenishing the weed seed bank (Norris 2007). Since many annual weed species are prolific seed producers, reducing the number of plants capable of producing viable seeds is essential to managing weed seed banks. In Alberta, scentless chamomile (*Matricaria perforata* Mérat) can produce between 71, 000 and 256,000 seeds plant^{-1} (Blackshaw and Harker 1997), depending upon environmental conditions and time of emergence; as a result, scentless chamomile populations can increase quickly if not managed carefully. The magnitude of seed production is influenced by many factors including weed and crop species (Clay et al. 2005; Davis 2008; Holman et al. 2006; Lutman 2002), crop seeding rate (O'Donovan et al. 2007b), time of weed emergence (Blackshaw and Harker 1997) and soil fertility (O'Donovan et al. 2008; Van Delden et al. 2002). Since weed escapes can maintain or intensify weed populations, reducing or eliminating seed production can help manage weed seed banks. After reducing weed seed production for 6 years in continuous corn, Schweizer and Zimdahl (1984) reported seed bank declines up to 98%, from 1.3 billion seeds ha^{-1} to 21 million seeds ha^{-1}; however discontinuing herbicide applications for three years resulted in replenishing the seed bank to 648 million seeds ha^{-1} or 50% of the initial population. Burnside et al. (1986) also reported similar results in continuous corn, whereby eliminating seed production reduced the seed bank by 95% over 5 years. After one year of discontinuing herbicide applications, seed bank densities were 90% of the initial population. Consequently, minimizing the addition of new weed seeds can reduce the weed seed reservoir, but a variety of factors contribute to the longevity of these seeds in the seed bank.

2.2.2. Dormancy, Germination and Emergence

Dormancy, germination and emergence are important processes that regulate seed banks. Weed seed populations benefit from dormancy as a condition that permits sporadic germination and persistent seed banks (Bewley 1997). The annual additions and losses of weed seeds from the soil seed bank in addition to variable levels of dormancy among a seed population contribute to the complexity and difficulty in predicting germination and emergence (Allen et al. 2007; Batlla and Benech-Arnold 2007; Benech-Arnold et al. 2000; Forcella et al. 2000). Seed dormancy has been defined as a characteristic or an internal condition of a seed, whereby the degree of dormancy establishes a range of hydric, thermal and gaseous conditions for germination (Benech-Arnold et al. 2000; Vleeshouwers et al. 1995). Despite numerous classification systems for seed dormancy (Baskin and Baskin 2004; Harper 1977; Vegis 1964), for the purpose of this review, the classification of primary and secondary dormancy defined by Karssen (Karssen 1980/1981b; Karssen 1982) will be used. Several researchers have addressed environmental, physiological, molecular and genetic factors that induce and alleviate primary and secondary dormancy (Allen et al. 2007; Baskin and Baskin 1998; Baskin and Baskin 2004; Bentsink et al. 2007; Bewley 1997; Finch-Savage and Leubner-Metzger 2006; Finkelstein et al. 2008; Foley 2001; Hilhorst and Toorop 1997; Hilhorst 2007; Koornneef et al. 2002; Li and Foley 1997). Although research is accumulating on mechanisms of dormancy, there is a deficiency in the amount of knowledge pertaining to dormancy cycling in weed seed banks and an inability to accurately predict weed seed germination and emergence under field conditions (Batlla et al. 2004; Benech-Arnold et al. 2000).

Weed seeds dispersed from the mother plant can have innate dormancy referred to as primary dormancy (Karssen 1980/1981a; Karssen 1982). Dormancy may be found in the embryo or the maternal tissues surrounding the embryo, such as the endosperm or perisperm (Baskin and Baskin 2004). Unlike annual weeds, annual crops have been selected for non-dormancy or reduced dormancy to promote synchronous germination. Many cereal crop species do not exhibit an innate dormancy in the embryo but have a short period of dormancy imposed by structures surrounding the embryo, including the endosperm, pericarp and glumellae which prevent pre-harvest sprouting (Benech-Arnold et al. 1999; Benech-Arnold 2004).

A period of after-ripening or stratification (a.k.a cold after-ripening or moist chilling) is typically needed to release primary dormancy. During after-ripening, seeds undergo dormancy release when exposed to dry, stable environmental conditions; however, the rate of after-ripening is largely dependent on temperature (Allen et al. 2007). Generally, winter annual weeds, including sheperd's purse [*Capsella bursa-pastoris* (L.) Medik], chickweed [*Stellaria media* (L.) Vill.], flixweed and downy brome require a period of after-ripening to release primary dormancy (Allen et al. 1995; Baskin and Baskin 1986; Li et al. 2005); however, some annual grass species also require a period of after-ripening, including wild oat (Foley 1994) and barley (Favier 1995). The extended periods of hot, dry summer temperatures followed by fall precipitation can release primary dormancy and permit germination in either late fall or early spring. Alternatively, during stratification, seeds are exposed to moist conditions under low temperatures with adequate oxygen. For many summer annual weed species in temperate regions, stratification is an integral process that alleviates primary dormancy (Probert 2000); consequently, periods of low temperatures during winter release primary dormancy to allow for spring germination. The stratification period can vary in the length of time (Baskin et al. 1992; Bello et al. 1998) and among weed species, populations and individual seeds (Andersson and Milberg 1998; Milberg and Andersson 1998). Stratification can also increase the sensitivity to other dormancy breaking stimulants, such as nitrate and light (Hilhorst et al. 1986). The release of primary dormancy can be further complicated in seed populations that require both after-ripening and stratification (Watanabe et al. 2002).

Secondary dormancy can be induced in non-dormant seeds when environmental conditions are not conducive for germination or re-induced in seeds that have previously achieved a low level of dormancy (Karssen 1980/1981a; Karssen 1982). The release of primary dormancy followed by the induction and re-induction of secondary dormancy creates an opportunity for dormancy cycling (Baskin and Baskin 1985; Karssen 1980/1981b). Consequently, a single generation of seeds may experience dormancy cycling for several years before germination and emergence occur (Forcella et al. 2000). Generally, dormancy is alleviated in the season prior to the period of favourable environmental conditions, whereby germination is stimulated during conditions that favour weed seedling growth and survival. For example, various summer annual weed species enter the fall seed bank exhibiting a high level of primary dormancy; although dormancy relief can occur during the winter followed by spring germination and emergence, some seeds can enter a state of secondary dormancy during summer (Figure 2.2.) (Batlla and Benech-Arnold 2007; Benech-Arnold et al. 2000). Winter annual weed species show the opposite trend. In temperate regions not limited by moisture, the dormancy cycle of many weed species is primarily regulated by temperature (Batlla et al. 2004); however, evidence suggests base water potential may influence the effect of temperature on dormancy alleviation and induction (Batlla et al. 2004; Batlla and Benech-Arnold 2007; Bauer et al. 1998). Low temperatures in winter release secondary dormancy in summer annuals and induce dormancy in winter annuals; conversely, high temperatures during summer release dormancy in winter annuals and induce dormancy in summer annuals (Batlla et al. 2004). In general, dormancy cycling is an important characteristic of weed species that promotes the survival and success of seedlings in harsh and unpredictable environments.

Primary and secondary dormancy may be physiologically and mechanistically different in weed species (Cadman et al. 2006; Vleeshouwers et al. 1995) but similar environmental stimuli are responsible for modulating these processes (Adkins and Simpson 1988; Karssen 1982). Furthermore, the role of environmental conditions such as fluctuating temperatures, light quality and nitrate, which alleviate and induce dormancy, may not differ from conditions that stimulate germination. As a result, the transition between dormancy and germination has added to the difficulty in studying dormancy (Hilhorst 2007).

For many weed seeds in the soil seed bank the degree of dormancy varies over a continuum. A range of environmental conditions that terminate dormancy (primary and secondary) and stimulate germination are influenced by the degree of dormancy (Benech-Arnold et al. 2000) (Figure 2.3.). At low dormancy levels seeds are sensitive to environmental factors that terminate dormancy and initiate germination (Benech-Arnold et al. 2000). Alternatively, seed populations exhibiting a high level of dormancy are less sensitive to environmental changes. As seed populations begin to exhibit low levels of seed dormancy the range of environmental conditions that permit germination broadens, whereas at high levels of dormancy the range of environmental conditions narrows until germination cannot occur (Batlla et al. 2004; Batlla and Benech-Arnold 2007). For example, in summer annual weeds, such as prostrate knotweed (*Polygonum aviculare* L.) (Figure 2.3.), seeds experiencing low levels of dormancy would be sensitive to a wide range of temperatures and water potentials thereby releasing dormancy and permitting germination; alternatively, a seed population experiencing a high level of dormancy would be less sensitive to factors that terminate dormancy, and only a narrow range of temperatures and water potentials could permit germination (Batlla and Benech-Arnold 2003; Batlla and Benech-Arnold 2004).

The degree of dormancy in weed seeds is also influenced by the physiological and physical status of the seed (Allen et al. 2007). For example, the genetic composition, age, maternal environment and position on mother plant during development are physiological factors that influence dormancy level (Andersson and Milberg 1998; Li and Foley 1997; Matilla et al. 2005). Physical factors of the seed, such as the permeability and strength of the seed coat, can influence the environmental stimuli regulating dormancy and germination (Allen et al. 2007; Matilla et al. 2005).

As environmental conditions permit the termination of dormancy and promotion of germination, seedling emergence (recruitment) can occur. Weed seedling emergence has three processes: seed germination, root elongation and shoot elongation. Each process is driven by different environmental stimuli

(Roman et al. 1999; Roman et al. 2000). Seed germination is one of the most well studied phenomena in plant development (Baskin and Baskin 1998; Egley 1986; Finch-Savage and Leubner-Metzger 2006; Hilhorst and Toorop 1997; Koornneef et al. 2002; Nonogaki et al. 2007; Riemens et al. 2004). Germination *sensu stricto* begins with the uptake of water (imbibition) by a dry seed and terminates once the embryo, typically the radicle, emerges through surrounding tissues (Nonogaki et al. 2007). The primary factors required for germination include temperature, water and oxygen; however, seeds may be stimulated by other factors including nitrate, light quality and ethylene (Egley 1986). Root (radicle) and shoot elongation are primarily regulated by temperature (Roman et al. 1999).

Several factors influence seedling emergence including weed species (Blackshaw et al. 2002a; Blackshaw 2003; Bouwmeester and Karssen 1993; Boyd and Van Acker 2003; De Corby et al. 2007; Lawson et al. 2006), seed size (Buhler 1995; Chauhan et al. 2006c), seed age (Martinkova et al. 2006; Roberts 1964), soil granulometric composition (Benvenuti 2003), environmental conditions (Boyd and Acker 2004a; Boyd and Van Acker 2004b; Bradford 2002; Grundy and Mead 2000; Page et al. 2006) and tillage regime (Benvenuti 2003; Bullied et al. 2003; Chauhan et al. 2006a; Chauhan et al. 2006b; Norsworthy and Oliveira 2007; Van Acker et al. 2004).

Tillage regimes play an important role in modulating the level of weed germination and seedling emergence. Timing and tillage regime influence the distribution of seeds in the soil profile as well as the microenvironment near the seed (Spandl et al. 1998; Yenish et al. 1996); however, tillage can also indirectly influence dormancy levels through fluctuations in soil temperature and moisture or modifying nitrate concentrations (Benech-Arnold et al. 2000). In no-till soils, seed is distributed within the top 5 cm of soil (Clements et al. 1996). As a result, weed seeds on or near the soil surface are exposed to frequent or early spring temperature fluctuations, which can create conditions for dormancy release and stimulation of germination (Forcella et al. 2000).

Dehydration/hydration cycles can also act as a dormancy breaking mechanism (Batlla and Benech-Arnold 2006; Kagaya et al. 2005); however, fluctuations in moisture content can also decrease seed viability (Śliwińska and Jendrzejczak 2002) and induce secondary dormancy (Downs and Cavers 2000). Large seeds near the soil surface are at risk of becoming dehydrated than smaller seeds or more deeply buried large seeds buried (Buhler 1995).

Tillage influences the distribution and size of soil aggregates as well as the variety and number of heterogenous seed-soil microsites (Pareja and Staniforth 1985); therefore, variability in the seed-soil microsites can affect seed dormancy and germination. In addition, seeds buried deeply by tillage may not have enough energy reserve for the hypocotyl to elongate and sufficiently emerge, resulting in pre-seedling mortality (fatal germination). Compact soils or soils that form a thin crust can impede emergence, resulting in pre-seedling mortality; however, some weed species have evolved structures that improve emergence in various soil conditions. For example, *Amaranthus retroflexus* (L.) emerges with reflexed cotyledons, the base of the cotyledons form a point at the tip of the hypocotyl (Forcella et al. 2000). Conversely, deeply buried seeds may induce secondary dormancy to minimize fatal germination. For example, some genotypes of volunteer canola buried deep (10 cm) can enter secondary dormancy (Gulden et al. 2004), resulting in a persistent seed bank (Gulden et al. 2003b).

In addition to tillage regime, other crop production practices can influence seed emergence. Addition of nitrogen fertilizers alters the concentration of nitrate in the soil, which can release dormancy and stimulate germination (Benech-Arnold et al. 2000; Dyer 1995). Incorporating crop residues with high C:N ratio can immobolize nitrogen, which can minimize nitrate needed to stimulate weed emergence (Benech-Arnold et al. 2000; Dyer 1995). Higher crop residues may also lower soil temperature and amount of light penetrating to the soil surface (Page et al. 2006). Understanding factors that alter dormancy status and seedling emergence can improve the timing of weed management strategies (Grundy 2003).

2.2.3. Seed Losses

A large proportion of seeds are removed from the soil seed bank through germination; however, seed banks can also be depleted through exposure to environmental stresses, seed aging, predation and microbial decay (Gallandt et al. 2004). In seeds, the endosperm provides a nutritional source of starches, oils and protein for seed predators and soil microorganisms. Various vertebrates and invertebrates have been identified in postdispersal predation, such as birds, insects and rodents. Typically, invertebrates consume more weed seeds than vertebrates in agricultural communities (Cromar et al. 1999; Gallandt et al. 2005). Damage to seeds by seed predators can also create an opportunity for fungal and bacterial infections thus reducing seed viability. Seed borne and soil borne fungi can have an additive effect, increasing seed losses from the soil seed bank (Kiewnick 1964 in Wagner and Mitschunas 2008). Soil fungi may access carbohydrates and amino acids from the seed to promote spore germination and hyphal growth. In some cases, soil bacteria and fungi can release toxins that damage seeds and/or inhibit weed seed germination (Harman 1983). For example, bacterial isolates extracted from the rhizosphere of winter wheat and downy brome suppressed downy brome root growth (Kennedy et al. 1991). Furthermore, seed mortality from microbial decay may be enhanced in soils enriched with inorganic nitrogen (Davis 2007). Some seeds have chemical protection mechanisms such as secondary metabolites (for example, phenols and alkaloids) and/or physical protection mechanisms such as hard, thick seed coats to maintain seed viability and structural integrity (Davis 2008; Kremer 1986; Mohamed-Yasseen et al. 1994).

Despite protection mechanisms to defend against seed predation and microbial attack, the maximum longevity of a seed is determined by its aging rate (Davis et al. 2008). The aging rate of seeds varies among weed species and soil conditions (Burnside et al. 1996; Conn and Deck 1995; Conn and Farris 1987; Conn et al. 2006; Egley and Chandler 1978; Telewski and Zeevaart 2002; Toole and Brown 1946). Seed aging is a gradual process that leads to loss of seed vigour and viability (McDonald 1999; Priestley 1986). In many cases it is difficult to separate loss of viability due to seed aging or microbial degradation. The loss of turgor and increased leakage of solutes from decaying seeds can increase seed vulnerability to fungal and bacterial infections (Kremer 1993). Environmental stresses such as freeze/thaw and dessication/rehydration cycles can also reduce seed vigor (Gallagher and Fuerst 2006). Seed reductions from the soil seed bank of direct seeded systems are linked to increased exposure to inhospitable environmental conditions (Murphy et al. 2006), such as extreme temperatures or moisture levels. Exposure of seeds to extreme wet conditions can weaken seed coats of hard seeds, increasing the vulnerability to fungal decay (Mickelson and Grey 2006; Schutte et al. 2008). Despite the complex interaction of seed mortality factors, each process plays an integral component in regulating weed seed losses from the soil seed bank.

Management practices may have an important role in enhancing seed mortality. Seeds on the soil surface, in the soil litter layer or mixed with other substrates, such as manure, can be at risk for predation compared to seeds buried deep in the soil profile. However, predation will vary among weed species, whereby small weed seeds that penetrate cracks in the soil or are washed away with rain endure less intense predation than large seeds remaining on the soil surface (Thompson 1987). Nevertheless, there is conflicting evidence regarding the impact of tillage regime on seed predation. Cardina et al. (1996) reported equal rates of velvet leaf seed predation in continuous no-tillage and mouldboard plow corn fields. Conversely, Menalled et al. (2007) reported two to three time higher activity-densities in no-till than in conventional or organic cropping systems among seed predating carabid species. Alternatively, predation rates can vary across tillage treatments. Seed predation of lamb's quarter and barnyard grass [*Echinochloa crus-galli* (L.) P. Beauv.] in a corn-soybean rotation averaged 32% in both no till and moldboard plow treatments and 24 % in chisel-plowed plots (Cromar et al. 1999). In addition, crop rotations create an opportunity to diversify cropping systems, while supporting a variety of predator species. Abundant seed predator diversity and seed predation has been reported in cropping systems that utilize cover crops or living mulches. Daily seed removal of giant foxtail (*Setaria faberi* Herrm) in wheat intercropped with red clover was greater than removal in a sole wheat crop (Davis and Liebman 2003). Similar results from Prasifka et al. (2006) show higher levels of predation and predator abundance when combining alfalfa and kura clover (*Trifolium ambiguum* M. Bieb.) mulches in corn and soybean than growing mulches alone.

Although management practices are influential on the level of predation (Cromar et al. 1999; Davis and Liebman 2003; Gallandt et al. 2005; Mauchline et al. 2005; Menalled et al. 2000; O'Rourke et al. 2006; Westerman et al. 2003a; Westerman et al. 2003b), there are various interacting factors that are also important, including feeding preferences (White et al. 2007), food availability (Cromar et al. 1999), seed aggregation (Marino et al. 2005), environmental factors (Zhang et al. 1997), plant phenology and physiology (Harrison et al. 2003; Hulme 1998), mobility of invertebrates (Cromar et al. 1999) and type of predator (vertebrate or invertebrate) (Cromar et al. 1999; Holmes and Froud-Williams 2005; Marino et al. 1997). Consequently, seed predation is composed of complex weed-predator interactions that can have a significant impact on the ecological processes within the weed seed bank (Menalled et al. 2006).

In contrast to the significant role of seed predation, only a small proportion of seeds in the soil seed bank are degraded by fungi or bacteria (Kremer 1993). The susceptibility to fungal or bacterial infection varies among seeds and microorganisms. Consequently, the variability in microbial-mediated decay can be attributed to a variety of interacting abiotic and biotic factors as well as the inherent characteristics of both seed and microbial populations (Chee-Sanford et al. 2006). Pitty et al. (1987) compared fungal colonization of green foxtail and giant foxtail seeds from three soil depths under plowed and reduced tillage regimes. Under reduced tillage greater fungal caryopsis colonization occurred in the top soil layers (0-7.5cm) whereas plowed treatments had greater colonization in the deep soil layers (7.5cm to 15cm). Greater fungal colonization was attributed to the placement of crop residues, whereby reduced tillage kept residues within the top soil layers and plowed treatments buried residues at deeper soil depths. Alternatively, Gallandt et al. (2004) reported similar proportions of dead and decayed wild oat seeds between zero-tillage and conservation tillage treatments, which suggests the environment may have had a greater impact on seed mortality than the tillage system. However, knowledge pertaining to seed mortality from environmental stresses such as freeze/thaw and dessication/rehydration cycles is limited (Gallagher and Fuerst 2006).

The proportion of seed mortality due to environmental stresses, seed aging, predation and microbial decay remain difficult to study and have been rarely categorized (Gallandt et al. 2004). Seed burial studies have been conducted to determine the longevity of seeds in the soil seed bank under various soil conditions (Burnside et al. 1996; Conn and Deck 1995; Conn and Farris 1987; Conn et al. 2006; Egley and Chandler 1978; Telewski and Zeevaart 2002; Toole and Brown 1946). Despite the practical nature of seed burial studies, they may overestimate seed bank depletion (Van Mourik et al. 2005) and seed longevity (Masin et al. 2006). The study of natural seed banks is difficult due to variability across time and space of various factors including seed size, species composition and seed depth (Benvenuti 2007). Nevertheless, research is needed to understand the role of seed mortality factors as well as mechanisms to enhance seed losses in western Canadian cropping systems.

2.3. Characteristics of Wild Oat Seed Banks in Western Canada

In western Canada, wild oat is an abundant annual grass weed found in agricultural fields. Recent weed surveys in Alberta (Leeson et al. 2002), Saskatchewan (Leeson et al. 2003) and Manitoba (Leeson 2002) indicate wild oat is present in 46 %, 51 % and 57 % of surveyed fields, respectively. Wild oat can cause economic losses from increased herbicide costs, yield and quality losses, dockage and reduced fertilizer utilization. Herbicide costs for managing wild oat in spring wheat, barley and canola in Western Canada exceed $500 million dollars annually (Leeson et al. 2006). In addition, an estimated $50 million dollars of lost yield occurs annually from residual wild oat populations (Leeson et al. 2006).

Wild oats can significantly reduce yields of barley (Morishita and Thill 1988; O'Donovan et al. 1985; O'Donovan et al. 1999b; O'Donovan et al. 2008; Scursoni and Satorre 2005), canola (Daugovish et al. 2002; Dew and Keys 1976; Zand and Beckie 2002), field peas (Harker et al. 2001), flax (Bell and Nalewaja 1968; Bowden and Friesen 1967), oats (Willenborg et al. 2005a; Willenborg et al. 2005b) and spring wheat (Carlson and Hill 1985; Kirkland and Hunter 1991; Kirkland 1993; O'Donovan et al. 2006a). Wild oat densities of 20 plants per m^2 will reduce barley, flax, spring wheat and canola yields 10%, 27%, 15% and 14% respectively (Dew 1972; Dew and Keys 1976). In addition to reduced yields, contamination by wild oats seeds can decrease crop quality by increasing dockage and reducing grain grade (Canadian Grain Commission 2009). Willenborg et al. (2005b) reported reductions in thousand kernel weight and kernel plumpness of tame oats as wild oat plant densities increased from 0 to 320 plants m^{-2}.

Management of wild oat is complicated by herbicide resistant genotypes, specifically group 1 (acetyl- CoA-carboxylase (ACCase) inhibitor), Group 2 (acetolactate synthase (ALS) inhibitor) or both Group 1 and 2 herbicide-resistant genotypes (Beckie et al. 2008a). A survey of wild oat seed collected from 565 fields across the Canadian Prairies found 83 and 46 fields with group 1 and group 2 herbicide resistance, respectively (Beckie et al. 2008a). In addition, 1067 wild oat seed samples collected from growers across western Canada between 1996 and 2006 confirmed Group 1 herbicide resistance in 725 samples, Group 2 resistance in 34 samples and resistance to both Group 1 and 2 herbicides in 55 samples (Beckie et al. 2008a). In a field, the distribution of herbicide resistant biotypes is typically non-uniform, occurring in small, stable patches (<0.4ha) (Beckie et al. 2005). Mixtures of resistant and susceptible plants are commonly found in herbicide resistance patches whose proportion is a function of selection pressure, seed production, seed rain, seed bank longevity, seed germination and seedling emergence (Beckie et al. 2002; Beckie et al. 2005; O'Donovan et al. 1999a).

Seed production and seed rain create an opportunity to replenish seed banks and sustain annual infestations. Wild oat seed production has been shown to vary by crop species and density as well as wild oat plant density. Sharma and Vanden Born (1978) reported wild oat seed production under no crop competition to average between 100 to 150 seeds per plant but some individual plants can produce 500 seeds per plant. Increased seeding rates and competitive crop cultivars can enhance crop competition to reduce wild oat densities and seed production. O'Donovan et al. (1999b) reported that increasing barley densities from 150 to 250 plants m^{-2} under wild oat densities of 100 plants m^{-2} reduced wild oat seed inputs from 1030 to 630 seeds m^{-2}, respectively. Management practices such as the amount of seed placed nitrogen or application of in-crop herbicide can have significant impact on wild oat seed production and seed bank densities. A six-fold increase in wild oat seed production occurred in barley between the lowest (0 kg N ha^{-1}) and highest (120 kg N ha^{-1}) seed placed nitrogen rates

(O'Donovan et al. 2008). Higher wild oat fecundity at the higher N rates was attributed to a reduction in barley stand. As a result, increasing barley seeding rate from 200 to 300 to 400 seeds m^{-2} increased barley plant density by 24 and 35%, respectively, as well as reduced wild oat fecundity by 23 and 44%, respectively (O'Donovan et al. 2008). Furthermore, increasing wheat seeding rate from 75 kg ha^{-1} to 150 kg ha $^{-1}$ while increasing the imazamethabenz rate from quarter to full rates reduced the amount of wild oat seeds returned to the seed bank (O'Donovan et al. 2006a). At full herbicide rates, the increase in wheat seeding rate decreased wild oat seed bank densities from 253 to 106 seeds m^{-2} (O'Donovan et al. 2006a). Integrating weed management practices, such as higher seeding rates and strategic fertilizer placement, are instrumental in reducing wild oat seed production and subsequent seeds present in the soil seed bank (Blackshaw et al. 2008).

Wild oat seed additions typically occur prior to crop maturity. The proportion of wild oat seeds remaining on the panicle largely depends on the harvest date (Shirtliffe et al. 2000) as well as environmental conditions prior to harvest, such as temperature and moisture (Barroso et al. 2006). In Western Canada, Shirtliffe et al. (2000) determined 80% of wild oat seed shatters prior to spring wheat harvested at 20% moisture. Seed that does not shatter prior to or during harvest may either be retained with the crop as a contaminant, or be separated from the harvested product and returned to the field. Chaff collection at harvest can be an effective method in reducing the amount of wild oat seed dispersed (Shirtliffe and Entz 2005) but may not be practical for large areas.

Although early wild oat seed shatter minimizes dispersal of seeds during harvest (Shirtliffe et al. 2000), it maximizes the opportunity to replenish the seed bank.

Wild oat seed dormancy research has been characterized through various environmental (Armstrong and Adkins 1998; Hilton 1985; Hilton and Bitterli 1983; Hsiao and Simpson 1971; Peters 1982; Sawhney and Naylor 1980; Sawhney and Naylor 1982; Sharma et al. 1976; Simpson 1990), physiological (Adkins and Ross 1981; Adkins et al. 1984a; Adkins et al. 1984b; Adkins et al. 1984c; Adkins et al. 1984d; Adkins et al. 1985; Adkins and Simpson 1988; Adkins et al. 1988; Cairns and Devilliers 1986; Cranston et al. 1996; Foley 1987; Foley 1992; Hilton 1984; Hou and Simpson 1993; Hou et al. 1997; Metzger 1983; Upadhyaya et al. 1982; Upadhyaya et al. 1983), molecular (Dyer 1993; Johnson and Dyer 2000; Li and Foley 1994; Li and Foley 1995; Li and Foley 1996) and genetic (Adkins et al. 1986; Armstrong and Adkins 1998; Fennimore and Foley 1998; Fennimore et al. 1998; Fennimore et al. 1999; Jana and Naylor 1980; Sawhney and Naylor 1979) studies. Despite extensive research, the physiological basis for dormancy in wild oat remains unknown. The factors that affect the induction and release of dormancy states still remain inconclusive, and sometimes contradictory. In many cases, dormancy experiments have been conducted under non-uniform conditions, whereby seeds are acquired from different biotypes, maternal environments or seed handling and storage conditions; therefore, while individual experiments are useful to understanding dormancy mechanisms, extrapolating from these experiments is difficult.

A complex set of seed-environment interactions govern seed dormancy in wild oat. In general, wild oat seeds exhibit primary and secondary dormancy, with a period of after-ripening (warm, dry conditions) to alleviate primary dormancy (Myers et al. 1997). The degree of dormancy found among wild oat seed populations is influenced by a range of environmental and genetic interactions. For instance, natural wild oat seed populations can express a range of dormancy phenotypes ranging from nondormant to highly dormant (Adkins et al. 1986). The nature of the genes that regulate dormancy still remains rather unclear; however, at least three loci are involved in regulating the expression of a dormant phenotype (Fennimore et al. 1999). In addition, various environmental conditions such as ambient air temperature (Sawhney and Naylor 1980), soil moisture (Sawhney and Naylor 1982) and photoperiod (Armstrong and Adkins 1998) will influence the degree of dormancy while a seed is developing, as well as its ability to be released from a dormant state. Chemical promoters such as potassium nitrate (Hilton 1984), ethylene (Adkins and Ross 1981; Cranston et al. 1996), gibberellic acid (Metzger 1983) and sodium azide (Upadhyaya et al. 1982) have been used to identify the physiological mechanism(s) involved in alleviating primary and secondary dormancy in wild oat seeds. Furthermore, piercing at the midpoint on the dorsal side of a wild oat caryopsis (Foley 1987) or scarification via a mechanical incision near the scutellum, or chemical scarification such as using an alkaline substance (KOH) (Hou et al. 1997) have also been identified in breaking primary dormancy.

Although the mechanisms behind dormancy are unclear, secondary dormancy plays an integral part in modulating wild oat seedling emergence and seed bank persistence. In addition to dormancy, genetic variations within a population, seed age, weed management strategies and environmental cues such as light, soil temperature and soil moisture will also influence seed germination and seedling emergence. Under field conditions, wild oat seedlings will emerge over a wide range of soil moisture and soil temperatures; however, the optimal conditions for emergence may vary due to genetic variation among distinct populations (Sharma and Vanden Born 1978). Friesen and Shebeski (1961) reported optimal air temperatures for emergence to occur between 15°C and 21°C; whereas Sharma et al. (1976) found maximum emergence to occur at air temperatures between 10°C and 21°C, whereby temperatures greater than 27°C noticeably reduced emergence. Similarly, Banting (1974) showed successful emergence to occur between 10°C and 27°C, with 83% germination occurring in 5 days at 10°C.

Although emergence increases with increasing temperatures, wild oat can germinate under low soil moisture conditions, whereby germination is not curtailed until water potential approaches -1200 kPA (Fernandez-Quinantilla et al. 1990). Maximum seedling emergence occurs when soil moisture is between 50 to 75% field capacity (Sharma et al. 1976). Similarly, Page et al. (2007) reported greater wild oat emergence across landscapes that acquired greater solar radiation, when soil moisture remained at field capacity. However, as soil moisture increases, linear increases in summer seed mortality and annual declines in seed bank numbers can occur (Mickelson and Grey 2006). Light quality and water status can also regulate wild oat seed germination. Hsiao and Simpson (1971) found that a combination of low water potential with white, red, blue or far red light can inhibit wild oat germination compared to seeds kept in darkness; however, wild oat seeds under a high water potential can germinate under white light conditions compared toseeds in dark, red, blue or far red light conditions. Combining information on soil temperature and soil moisture with secondary dormancy research can aid in predicting peak times of wild oat emergence, thereby improving the timing of in-crop herbicide applications (Martinson et al. 2007).

Cohorts of wild oat seed that enter the soil seed bank can persist for 4 to 6 years (Banting 1962; Banting 1966). However, conditions in the seed bank can influence the viability and longevity of seeds, including soil moisture and temperature, oxygen concentration and predation. Conn et al. (2006) reported wild oat seed viability rapidly declined by 80% in 3.7 years, with the greatest declines in seed viability occurring at a shallow depth (2 cm). Furthermore, wild oat seeds maintain higher rates of seed viability buried at deeper soil depths (> 12 cm) than at shallow soil depths (0-10 cm) (Miller and Nalewaja 1990). Under various tillage systems, the depth of burial has long term implications for wild oat populations.

Seeds buried through tillage can remain viable longer than seeds found near or on the soil surface (Banting 1966; Thurston 1961). In zero tillage, the persistence and viability of wild oat seeds may be lower since seeds on the surface can succumb to physiological decay, exhaustion, predation and fatal germination (Buhler et al. 1997a; Miller and Nalewaja 1990). Alternatively, Gallandt et al. (2004) found no difference between the level of microbial decay on wild oat between conservation tillage and no-tillage systems, suggesting similar levels of activity by microorganisms in each tillage regime. Mickelson and Grey (2006) reported a rapid decline of wild oat seeds under moist soils, whereby an increase in soil water content from 6 to 24%, increased wild oat seed mortality from 38 to 88% in 2001 and 53 to 79% in 2002. Consequently, increased soil moisture can favour the activity of soil microorganisms resulting in increased seed mortality. The study of seed predation on wild oat populations is very limited. No current research has identified the impact or the type of seed predators involved in reducing wild oat seed banks in western Canadian cropping systems. Consequently, further research is needed to address the management factors that promote wild oat seed losses through increased seed decay, microbial or fungal decay or predation.

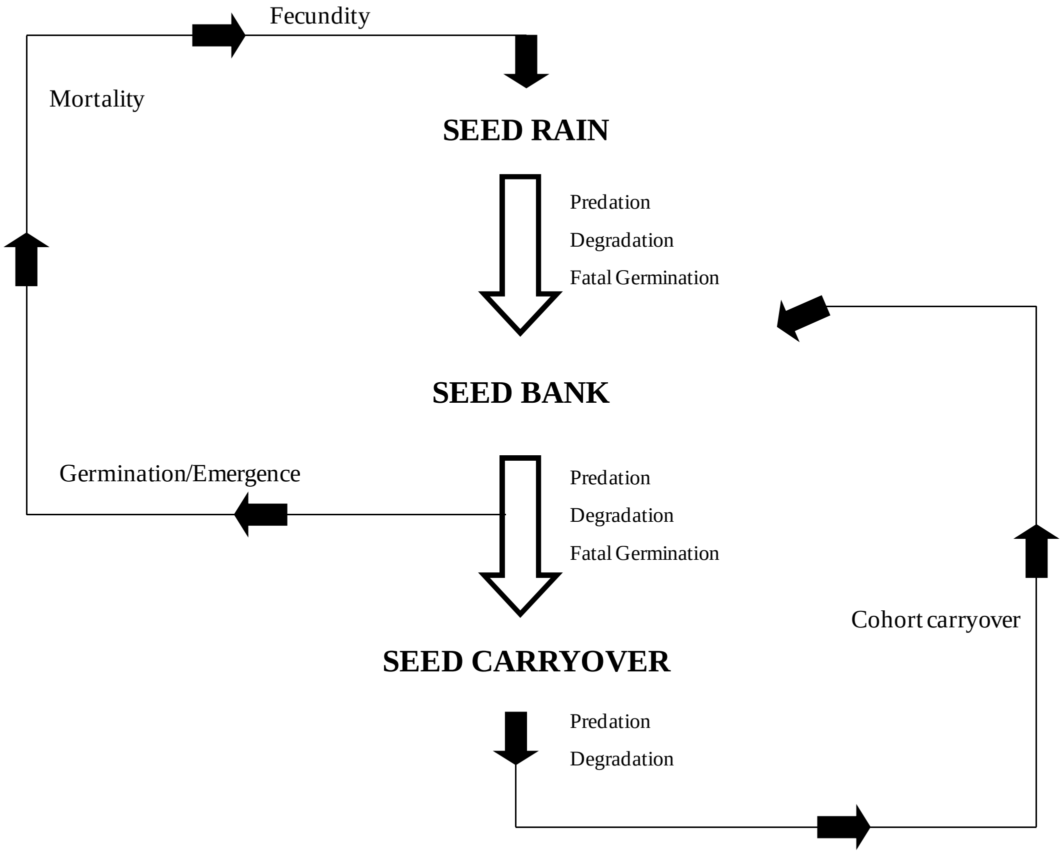

Figure 2.1. Weed seed cycle [Adapted from (Buhler et al. 1997a)].

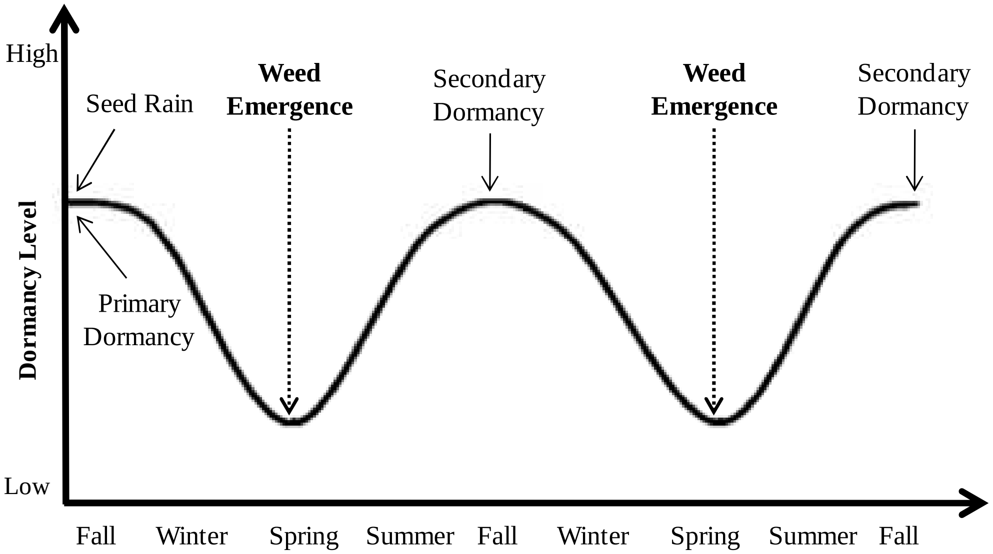

Figure 2.2. Dormancy cycling of an annual weed in the soil seed bank [Adapted from Batlla and Benech-Arnold (2007)].

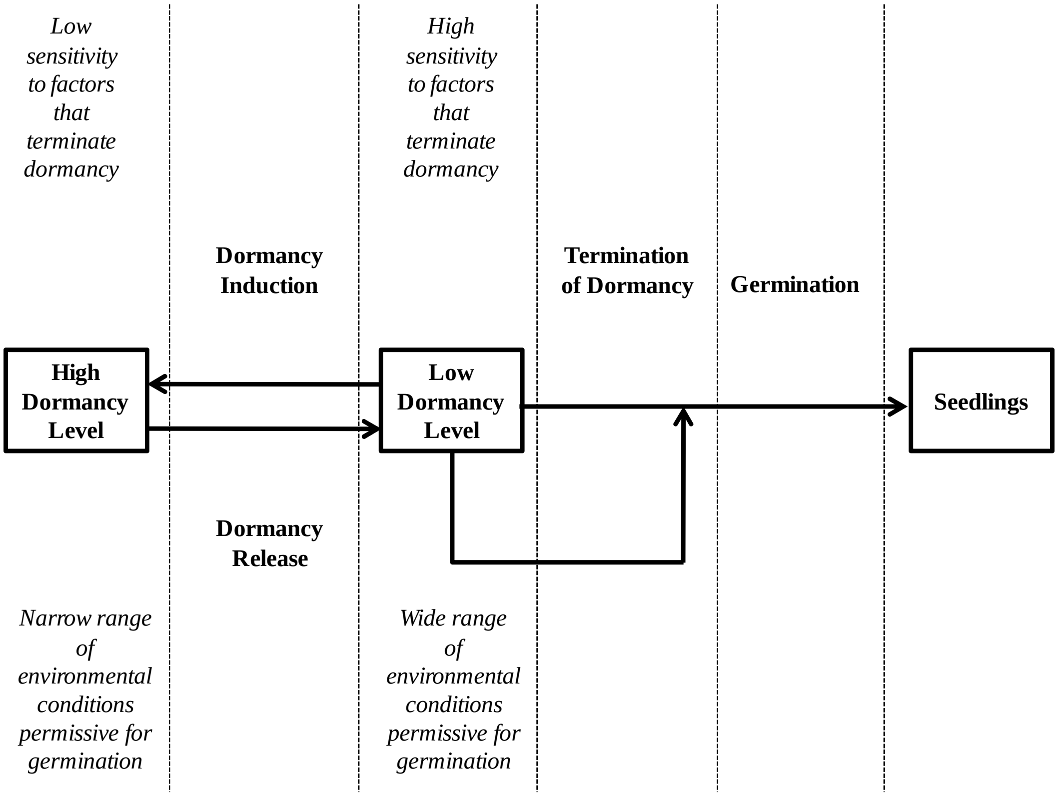

Figure 2.3. Flow chart depicting changes in dormancy level and termination of dormancy for a summer annual weed seed bank [Adapted from Benech-Arnold et al. (2000)].

2.4. Literature Cited

Adkins, S. W., M. Loewen, and S. J. Symons. 1986. Variation within pure lines of wild oats (*Avena fatua*) in relation to degree of primary dormancy. Weed Sci. 34:859-864.

Adkins, S. W., J. M. Naylor, and G. M. Simpson. 1984a. The physiological basis of seed dormancy in *Avena fatua*. V. Action of ethanol and other organic compounds. Physiol. Plantarum 62:18-24.

Adkins, S. W. and J. D. Ross. 1981. Studies in wild oat seed dormancy 1. The role of ethylene in dormancy breakage and germination of wild oat seeds (*Avena fatua* L.). Plant Physiol. 67:358-362.

Adkins, S. W. and G. M. Simpson. 1988. The physiological basis of seed dormancy in *Avena fatua.* IX. Characterization of two dormancy states. Physiologia Plantarum 73:15-20.

Adkins, S. W., G. M. Simpson, and J. M. Naylor. 1984b. The physiological basis of seed domancy in *Avena fatua*. VI. Respiration and the stimulation of germination by ethanol. Physiol. Plantarum 62:148-152.

Adkins, S. W., G. M. Simpson, and J. M. Naylor. 1984c. The physiological basis of seed dormancy in *Avena fatua*. III. Action of nitrogenous compounds. Physiol. Plantarum 60:227-233.

Adkins, S. W., G. M. Simpson, and J. M. Naylor. 1984d. The physiological basis of seed dormancy in *Avena fatua*. IV. Alternative respiration and nitrogenous compounds. Physiol. Plantarum 60:234-238.

Adkins, S. W., G. M. Simpson, and J. M. Naylor. 1985. The physiological basis of seed dormancy in *Avena fatua*. VII. Action of organic acids and pH. Physiol. Plantarum 65:310-316.

Adkins, S. W., S. J. Symons, and G. M. Simpson. 1988. The physiological basis of seed dormancy in *Avena fatua*. VIII. Action of malonic acid. Physiol. Plantarum 72:477-482.

Ali-Khan, S. T. 1977. Yield, seed weight, percent protein and protein yield of field peas as affected by seeding dates. Can. J. Plant Sci. 17-20.

Allen P. S., R. Benech-Arnold, D. Batlla, and K. J. Bradford. 2007. Modeling of seed dormancy. Pages 73-112 *In* K. J. Bradford and H. Nonogaki, eds. Seed Development, Dormancy and Germination. Ames, Iowa: Blackwell Publishing Limited.

Allen, P. S., S. E. Meyer, and J. Beckstead. 1995. Patterns of seed after-ripening in *Bromus tectorum* L. J. Exp. Bot. 46:1737-1744.

Anderson, R. 2003. An ecological approach to strengthen weed management in the semiarid Great Plains. Adv. Agron. 80:33-62.

Anderson, R. L. 2004. A planning tool for integrating crop choices with weed management in the Northern Great Plains. Renew. Agr. Food Syst. 19:23-29.

Anderson, R. L. 2005. A multi-tactic approach to manage weed population dynamics in crop rotations. Agron. J. 97:1579-1583.

Anderson, R. L. 2008. Weed seedling emergence and survival as affected by crop canopy. Weed Technol. 22:736-740.

Andersson, L. and P. Milberg. 1998. Variation in seed dormancy among mother plants, populations and years of seed collection. Seed Sci. Res. 8:29-38.

Angadi, S. V., H. W. Cutforth, B. G. McConkey, and Y. Gan. 2004. Early seeding improves the sustainability of canola and mustard production on the Canadian semiarid Prairie. Can. J. Plant Sci. 84:705-711.

Armstrong, L. J. and S. W. Adkins. 1998. Variation in photoperiod response of different isogenic lines of wild oats (*Avena fatua*). Weed Sci. 46:39-47.

Arshad, M. A., A. J. Franzleubbers, and R. H. Azooz. 1999. Components of surface soil structure under conventional and no-tillage in northwestern Canada . Soil Tillage Res. 53:41-47.

Azooz, R. H. and M. A. Arshad. 1996. Soil infiltration and hydraulic conductivity under long-term no-tillage and conventional tillage systems. Can. J. Soil Sci. 76:143-152.

Azooz, R. H. and M. A. Arshad. 1998. Effect of tillage and residue management on barley and canola growth and water use efficiency. Can. J. Soil Sci. 78:649-656.

Banting, J. D. 1962. The dormancy behavior of *Avena fatua* L. in cultivated soil. Can. J. Plant Sci. 42:22-39.

Banting, J. D. 1966. Studies on the persistence of *Avena fatua*. Can. J. Plant Sci 46:129-140.

Banting, J. D. 1974. Growth habit and control of wild oats. Publ. Agric. Can. 1531. Pp.34.

Barroso, J., L. Navarrete, M. J. S. Del Arco, C. Fernandez-Quintanilla, P. J. W. Lutman, N. H. Perry, and R. I. Hull. 2006. Dispersal of *Avena fatua* and *Avena sterilis* patches by natural dissemination, soil tillage and combine harvesters. Weed Res. 46:118-128.

Baskin, J. M. and C. C. Baskin. 1985. The annual dormancy cycle in buried weed seeds: A continuum. Bioscience 35:492-498.

Baskin, J. M. and C. C. Baskin. 1986. Temperature requirements for after-ripening in seeds of nine winter annuals. Weed Res. 26:375-380.

Baskin C. C. and J. M. Baskin. 1998. Seeds: Ecology, biogeography, and evolution of dormancy and germination. San Diego, CA, USA: Academic Press. 666p.

Baskin, J. M. and C. C. Baskin. 2004. A classification system for seed dormancy. Seed Sci. Res. 14:1-16.

Baskin, C. C., J. M. Baskin, and G. R. Hoffman. 1992. Seed dormancy in the Prairie forb *Echinacea angustifolia* var. *angustifolia* (Asteraceae): Afterripening pattern during cold stratification. Int. J. Plant Sci. 153:239-243.

Batlla, D. and R. L. Benech-Arnold. 2003. A quantitative analysis of dormancy loss dynamics in *Polygonum aviculare* L. seeds: Development of a thermal time model based on changes in seed population thermal parameters. Seed Sci. Res. 13:55-68.

Batlla, D. and R. L. Benech-Arnold. 2004. A predictive model for dormancy loss in *Polygonum aviculare* L. seeds based on changes in population hydrotime parameters. Seed Sci. Res. 14:277-286.

Batlla, D. and R. L. Benech-Arnold. 2006. The role of fluctuations in soil water content on the regulation of dormancy changes in buried seeds of *Polygonum aviculare* L. Seed Sci. Res.16,:47-59.

Batlla, D. and R. L. Benech-Arnold. 2007. Predicting changes in dormancy level in weed seed soil banks: Implications for weed management. Crop Protect. 26:189-197.

Batlla D., B. C. Kruk, and R. L. Benech-Arnold. 2004. Modeling changes in dormancy in weed soil banks: implications for the prediction of weed emergence. Pages 245-264 *In* R. L. Benech-Arnold and R. A. Sánchez, eds. Handbook of Seed Physiology. Applications to Agriculture. New York: Haworth Press, Inc.

Bauer, M. C., S. E. Meyer, and P. S. Allen. 1998. A simulation model to predict seed dormancy loss in the field for *Bromus tectorum* L. J. Exp. Bot. 49:1235-1244.

Beckie, H. J., L. M. Hall, and B. Schuba. 2005. Patch management of herbicide-resistant wild oat (*Avena fatua*). Weed Technol. 19:697-705.

Beckie, H. J., K. N. Harker, L. M. Hall, S. I. Warwick, A. Legere, P. H. Sikkema, G. W. Clayton, A. G. Thomas, J. Y. Leeson, G. Seguin-Swartz, and M. J.

Simard. 2006. A decade of herbicide-resistant crops in Canada . Can. J. Plant Sci. 86:1243-1264.

Beckie, H. J., E. N. Johnson, R. E. Blackshaw, and Y. Gan. 2008. Weed suppression by canola and mustard cultivars. Weed Technol. 22:182-185.

Beckie, H. J. and K. J. Kirkland. 2003. Implication of reduced herbicide rates on resistance enrichment in wild oat (*Avena fatua*). Weed Technol. 17:138-148.

Beckie, H. J., J. Y. Leeson, A. G. Thomas, C. A. Brenzil, L. M. Hall, and G. Holzgang. 2008a. Weed resistance monitoring in the Canadian Prairies. Weed Technol. 22:530-543.

Beckie, H. J., A. G. Thomas, and F. C. Stevenson. 2002. Survey of herbicide-resistant wild oat (*Avena fatua*) in two townships in Saskatchewan. Can. J. Plant Sci. 82:463-471.

Bekker, R. M., J. P. Bakker, U. Grandin, R. Kalamees, P. Milberg, P. Poschlod, K. Thompson, and J. H. Willems. 1998. Seed size, shape and vertical distribution in the soil: Indicators of seed longevity. Funct. Ecol. 12:834-842.

Bell, A. R. and J. D. Nalewaja. 1968. Effect of duration of wild oat competition in flax. Weed Sci. 16:509-512.

Bello, I. A., H. Hatterman-Valenti, and M. D. K. Owen. 1998. Effects of stratification, temperature, and oxygen on woolly cupgrass (*Eriochloa villosa*) seed dormancy. Weed Sci. 46:526-529.

Benech-Arnold R. L. 2004. Inception, maintenance, and termination of dormancy in grain crops: Physiology, genetics, and environmental control. Pages 169-198 *In* R. L. Benech-Arnold and R. A. Sanchez, eds. Handbook of Seed Physiology: Applications to Agriculture. 1st ed. New York: The Haworth Press.

Benech-Arnold, R. L., M. C. Giallorenzi, J. Frank, and V. Rodriguez. 1999. Termination of hull-imposed dormancy in developing barley grains is correlated with changes in embryonic ABA levels and sensitivity. Seed Sci. Res. 9:39-47.

Benech-Arnold, R. L., R. A. Sanchez, F. Forcella, B. C. Kruk, and C. M. Ghersa. 2000. Environmental control of dormancy in weed seed banks in soil. Field Crops Res. 67:105-122.

Bentsink L., W. Soppe, and M. Koornneef. 2007. Genetic aspects of seed dormancy. *In* Bradford K.J. and Nonogaki H., eds. : Oxford, UK: Blackwell Publishing.

Benvenuti, S. 2003. Soil texture involvement in germination and emergence of buried weed seeds. Agron. J. 95:191-198.

Benvenuti, S. 2007. Natural weed seed burial: Effect of soil texture, rain and seed characteristics. Seed Sci. Res.17:211-219.

Bewley, J. D. 1997. Seed germination and dormancy. Plant Cell 9:1055-1066.

Blackshaw, R. E. 1994. Rotation affects downy brome (*Bromus tectorum*) in winter wheat (*Triticum aestivum*). Weed Technol. 8:728-732.

Blackshaw, R. E. 2003. Soil temperature and soil water effects on pygmyflower (*Androsace septentrionalis*) emergence. Weed Sci. 51:592-595.

Blackshaw, R. E., H. J. Beckie, L. J. Molnar, T. Entz, and J. R. Moyer. 2005a. Combining agronomic practices and herbicides improves weed management in wheat-canola rotations within zero-tillage production systems. Weed Sci. 53:528-535.

Blackshaw, R. E., R. N. Brandt, and T. Entz. 2002a. Soil temperature and soil water effects on henbit emergence. Weed Sci. 50:494-497.

Blackshaw, R. E., R. N. Brandt, H. H. Janzen, and T. Entz. 2004a. Weed species response to phosphorus fertilization. Weed Sci. 52:406-412.

Blackshaw, R. E., R. N. Brandt, H. H. Janzen, T. C. Entz, C. A. Grant, and D. A. Derksen. 2003. Differential response of weed species to added nitrogen. Weed Sci. 51:532-539.

Blackshaw, R. E. and K. N. Harker. 1997. Scentless chamomile (*Matricaria perforata*) growth, development, and seed production. Weed Sci. 45:701-705.

Blackshaw, R. E., K. N. Harker, J. T. O'Donovan, H. J. Beckie, and E. G. Smith. 2008. Ongoing development of integrated weed management systems on the Canadian Prairies. Weed Sci. 56:146-150.

Blackshaw, R. E. and L. J. Molnar. 2009. Phosphorus fertilizer application method affects weed growth and competition with wheat [electronic resource]. Weed Sci. 57:311-318.

Blackshaw, R. E., L. J. Molnar, and H. H. Janzen. 2004b. Nitrogen fertilizer timing and application method affects weed growth and competition with spring wheat. Weed Sci. 52:614-622.

Blackshaw, R. E., J. R. Moyer, R. C. Doram, and A. L. Boswell. 2001. Yellow sweetclover, green manure, and its residues effectively suppress weeds during fallow. Weed Sci. 49:406-413.

Blackshaw, R. E., J. R. Moyer, K. N. Harker, and G. W. Clayton. 2005b. Integration of agronomic practices and herbicides for sustainable weed management in a zero-till barley field pea rotation. Weed Technol. 19:190-196.

Blackshaw, R. E., G. Semach, and H. H. Janzen. 2002b. Fertilizer application method affects nitrogen uptake in weeds and wheat. Weed Sci. 50:634-641.

Blackshaw, R. E., G. P. Semach, and J. T. O'Donovan. 2000. Utilization of wheat seed rate to manage redstem filaree (*Erodium cicutarium*) in a zero-tillage cropping system. Weed Technol. 14:389-396.

Blackshaw, R. E., G. Semach, L. Xiangju, J. T. O'Donovan, and K. N. Harker. 1999. An integrated weed management approach to managing foxtail barley (*Horedeum jubatum*) in conservation tillage systems. Weed Technol. 13:347-353.

Blackshaw R. E., A. G. Thomas, D. A. Derksen, J. R. Moyer, P. R. Watson, A. Legere, and G. C. Turnbull. 2006. Examining tillage and crop rotation effects on weed populations in the Canadian Prairies. Pages 179-205 *In* P. S. Harminder, D. R. Batish and R. K. Kohli, eds. Handbook of Sustainable Weed Management. New York: Food Products Press.

Bouwmeester, H. J. and C. M. Karssen. 1993. Seasonal periodicity in germination of seeds of *Chenopodium album* L. Ann. Bot. 72:463-473.

Bowden, B. A. and G. Friesen. 1967. Competition of wild oats (*Avena fatua* L.) in wheat and flax. Weed Res. 7:349-359.

Box A. J., S. P. Jefferies, and A. R. Barr. 1999. Emergence and Establishment Problems of Hulless Barley – A Possible Solution. Available at: http://www.regional.org.au/au/abts/1999/box.htm. Accessed: January 1, 2009.

Boyd, N. S. and R. C. Van Acker. 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.

Boyd, N. S. and R. C. Van Acker. 2004a. Imbibition response of green foxtail, canola, wild mustard, and wild oat seeds to different osmotic potentials. Can. J. Bot. 82:801-806.

Boyd, N.S. and R. C. Van Acker. 2004b. Seed germination of common weed species as affected by oxygen concentration, light, and osmotic potential. Weed Sci. 52:589-596.

Bradford, K. J. 2002. Applications of hydrothermal time to quantifying and modeling seed germination and dormancy. Weed Sci. 50:248-260.

Brainard, D. C., A. Di Tommaso, and C. L. Mohler. 2007. Intraspecific variation in seed characteristics of powell amaranth (*Amaranthus powellii*) from habitats with contrasting crop rotation histories. Weed Sci. 55:218-226.

Briggs, K. G. and A. Aytenfisu. 1979. The effects of seeding rate, seeding date and location on grain yield, maturity, protein percentage and protein yield of some spring wheats in central Alberta. Can. J. Plant Sci. 59:1139-1145.

Buhler, D. D. 1995. Infleunce of tillage systems on weed population dynamics and management in corn and soybean in the central USA. Crop Sci 35:1247-1258.

Buhler, D. D., R. G. Hartzler, and F. Forcella. 1997a. Implications of weed seedbank dynamics to weed management. Weed Sci. 45:329-336.

Buhler, D. D., R. P. King, S. M. Swinton, J. L. Gunsolus, and F. Forcella. 1997b. Field evaluation of a bioeconomic model for weed management in soybean (*Glycine max*). Weed Sci. 45:158-165.

Bullied, W. J., A. M. Marginet, and R. C. Van Acker. 2003. Conventional- and conservation-tillage systems influence emergence periodicity of annual weed species in canola. Weed Sci. 51:886-897.

Burnside, O. C., R. S. Moomaw, F. W. Roeth, G. A. Wicks, and R. G. Wilson. 1986. Weed seed demise in soil in weed-free-corn (*Zea mays*) production across Nebraska. Weed Sci. 34:248-251.

Burnside, O. C., R. G. Wilson, S. Weisberg, and K. G. Hubbard. 1996. Seed longevity of 41 weed species buried 17 years in eastern and western Nebraska. Weed Sci. 44:74-86.

Cabin, R. J. 1996. Genetic comparisons of seed bank and seedling populations of perennial desert mustard, *Lesquerella fendleri*. Evolution 50:1830-1841.

Cabin, R. J., R. J. Mitchell, and D. L. Marshall. 1998. Do surface plant and soil seed bank populations differ genetically? A multipopulation study of the desert mustard *Lesquerella fendleri* (Brassicaceae). Am. J. Bot. 85:1098-1109.

Cadman, C. S. C., P. E. Toorop, H. W. M. Hilhorst, and W. E. Finch-Savage. 2006. Gene expression profiles of *Arabidopsis cvi* seeds during dormancy cycling indicate a common underlying dormancy control mechanism. The Plant Journal 46:805-822.

Cairns, A. L. P. and O. T. Devilliers. 1986. Physiological-basis of dormancy-breaking in wild oat (*Avena fatua* L.) seed by ammonia. Weed Res. 26:365-374.

Campbell, C. A., V. O. Biederbeck, M. Schnitzer, F. Selles, and R. P. Zentner. 1989. Effect of 6 years of zero tillage and N fertilizer management on changes in soil quality of an orthic brown chernozem in southwestern Saskatchewan. Soil Tillage Res. 14:39-52.

Campbell, C. A., B. G. McConkey, V. O. Biederbeck, R. P. Zentner, D. Curtin, and M. R. Peru. 1998. Long-term effects of tillage and fallow-frequency on soil quality attributes in a clay soil in semiarid southwestern Saskatchewan. Soil Tillage Res. 46:135-144.

Canadian Grain Commission. 2009. Official grain grading guide. Available at: http://www.grainscanada.gc.ca/oggg-gocg/ggg-gcg-eng.htm. Accessed: August 29, 2010.

Canola Council of Canada. 2003. Canola Growers Manual: Chapter 7 Soil Preparation. Available at: http://www.canola-council.org/chapter7.aspx#ch7_sec5. Accessed: May 10, 2009.

Cardina, J., C. P. Herms, and D. J. Doohan. 2002. Crop rotation and tillage system effects on weed seedbanks. Weed Sci. 50:448-460.

Cardina, J., H. M. Norquay, B. R. Stinner, and D. A. McCartney. 1996. Postdispersal predation of velvetleaf (*Abutilon theophrasti*) seeds. Weed Sci. 44:534-539.

Carlson, H. L. and J. E. Hill. 1985. Wild oat (*Avena fatua*) competition with spring wheat: Plant density effects. Weed Sci. 33:176-181.

Castillo, R. F. D. 1994. Factors influencing the genetic structure of *Phacelia dubia*, a species with a seed bank and large fluctuations in population size. Heredity 72:441-458.

Cavers, P. B. 1995. Seed banks: Memory in soil. Can. J. Soil Sci. 75:11-13.

Champion, G. T., R. J. Froud-Williams, and J. M. Holland. 1998. Interactions between wheat (*Triticum aestivum* L.) cultivar, row spacing and density and the effect on weed suppression and crop yield. Ann. Appl. Biol. 133:443-453.

Chauhan, B. S., G. Gill, and C. Preston. 2006a. Influence of environmental factors on seed germination and seedling emergence of rigid ryegrass (*Lolium rigidum*). Weed Sci. 54:1004-1012.

Chauhan, B. S., G. Gill, and C. Preston. 2006b. Influence of tillage systems on vertical distribution, seedling recruitment and persistence of rigid ryegrass (*Lolium rigidum*) seed bank [electronic resource]. Weed Sci. 54:669-676.

Chauhan, B. S., G. Gill, and C. Preston. 2006c. Seedling recruitment pattern and depth of recruitment of 10 weed species in minimum tillage and no-till seeding systems [electronic resource]. Weed Sci. 54:658-668.

Chee-Sanford, J. C., M. M. Williams, A. S. Davis, and G. K. Sims. 2006. Do microorganisms influence seed-bank dynamics? Weed Sci. 54:575-587.

Chen, C. C., G. Jackson, K. Neill, D. Wichman, G. Johnson, and D. Johnson. 2005. Determining the feasibility of early seeding canola in the Northern Great Plains. Agron. J. 97:1252-1262.

Clarke, J. M. 1985. Harvesting losses of spring wheat in windrower/combine and direct combine harvesting systems. Agron. J. 77:13-17.

Clay, S. A., J. Kleinjan, D. E. Clay, F. Forcella, and W. Batchelor. 2005. Growth and fecundity of several weed species in corn and soybean. Agron. J. 97:294-302.

Clayton, G. W., K. N. Harker, J. T. O'Donovan, M. N. Baig, and M. J. Kidnie. 2002. Glyphosate timing and tillage system effects on glyphosate-resistant canola (*Brassica napus*). Weed Technol. 16:124-130.

Clayton, G. W., K. N. Harker, J. T. O'Donovan, R. E. Blackshaw, L. M. Dosdall, F. C. Stevenson, and T. Ferguson. 2004. Fall and spring seeding date effects on herbicide-tolerant canola (*Brassica napus* L.) cultivars. Can. J. Plant Sci. 84:419-430.

Clements, D. R., D. L. Benoit, S. D. Murphy, and C. J. Swanton. 1996. Tillage effects on weed seed return and seedbank composition. Weed Sci 44:314-322.

Cohen, D. 1966. Optimizing reproduction in a randomly varying environment. J. Theor. Biol. 12:119-129.

Conn, J. S., K. L. Beattie, and A. Blanchard. 2006. Seed viability and dormancy of 17 weed species after 19.7 years of burial in alaska. Weed Sci. 54:464-470.

Conn, J. S. and R. E. Deck. 1995. Seed viability and dormancy of 17 weed species after 9.7 years of burial in alaska. Weed Sci. 43:583-585.

Conn, J. S. and M. L. Farris. 1987. Seed viability and dormancy of 17 weed species after 21 months in alaska. Weed Sci. 35:524-528.

Cousens, R., P. Brain, J. T. Odonovan, and P. A. Osullivan. 1987. The use of biologically realistic equations to describe the effects of weed density and relative-time of emergence on crop yield. Weed Sci. 35:720-725.

Cousens, R., C. J. Doyle, B. J. Wilson, and G. W. Cussans. 1986. Modeling the economics of controlling *Avena fatua* in winter wheat. Pestic. Sci. 17:1-12.

Cranston, H. J., A. J. Kern, S. A. Gerhardt, and W. E. Dyer. 1996. Wound-induced ethylene and germination of embryos excised from dormant *Avena fatua* L. caryopses. Int. J. Plant Sci. 157:153-158.

Cromar, H. E., S. D. Murphy, and C. J. Swanton. 1999. Influence of tillage and crop residue on postdispersal predation of weed seeds. Weed Sci. 47:184-194.

Cutforth, H. W., S. V. Angadi, and B. G. McConkey. 2006. Stubble management and microclimate, yield and water use efficiency of canola grown in the semiarid Canadian Prairie. Can. J. Plant Sci. 86:99-107.

Cutforth, H. W. and B. G. McConkey. 1997. Stubble height effects on microclimate, yield and water use efficiency of spring wheat grown in a semiarid climate on the Canadian Prairies. Can. J. Plant Sci. 77:359-366.

Cutforth, H. W., B. G. McConkey, D. Ulrich, P. R. Miller, and S. V. Angadi. 2002. Yield and water use efficiency of pulses seeded directly into standing stubble in the semiarid Canadian Prairie. Can. J. Plant Sci. 82:681-686.

Daugovish, O., D. C. Thill, and B. Shafii. 2002. Competition between wild oat (*Avena fatua*) and yellow mustard (*Sinapis alba*) or canola (*Brassica napus*). Weed Sci. 50:587-594.

Davis, A. S. 2007. Nitrogen fertilizer and crop residue effects on seed mortality and germination of eight annual weed species [electronic resource]. Weed Sci. 55:123-128.

Davis, A. S. 2008. Weed seed pools concurrent with corn and soybean harvest in Illinois. Weed Sci. 56:503-508.

Davis, A. S. and M. Liebman. 2003. Cropping system effects on giant foxtail (*Setaria faberi*) demography: I. Green manure and tillage timing. Weed Sci. 51:919-929.

Davis, A. S., K. A. Renner, J. Iannuzzi, and B. J. Schutte. 2008. Chemical and physical defense of weed seeds in relation to soil seedbank persistence [electronic resource]. Weed Sci. 56:676-684.

Davis, A. S., K. A. Renner, E. C. Luschei, M. M. Williams II, C. L. Sprague, J. L. Lindquist, F. Forcella, J. Cardina, G. Kegode, and G. A. Johnson. 2005. Environmental factors affecting seed persistence of annual weeds across the U.S. Corn Belt. Weed Sci. 53:860-868.

De Corby, K. A., R. C. Van Acker, A. Brûlé-Babel, and L. F. Friesen. 2007. Emergence timing and recruitment of volunteer spring wheat [electronic resource]. Weed Sci. 55:60-69.

Degenhardt, D. F. and Z. P. Kondra. 1981. The influence of seeding date and seeding rate on seed yield and yield components of five genotypes of *Brassica napus*. Can. J. Plant Sci. 61:175-183.

Derksen, D. A., R. L. Anderson, R. E. Blackshaw, and B. Maxwell. 2002. Weed dynamics and management strategies for cropping systems in the Northern Great Plains. Agron. J. 94:174-185.

Dew, D. A. 1972. An index of competition for estimating crop loss due to weeds. Can. J. Plant Sci. 52:921-927.

Dew, D. A. and C. H. Keys. 1976. An index of competition for estimating loss of rape due to wild oats. Can. J. Plant Sci. 1005-1006.

Di Tomaso, J. M. 1995. Approaches for improving crop competitiveness through the manipulation of fertilization strategies. Weed Sci. 43:491-497.

Downs, M. P. and P. B. Cavers. 2000. Effects of wetting and drying on seed germination and seedling emergence of bull thistle, *Cirsium vulgare* (Savi) Ten. Can. J. Bot. 78:1545-1551.

Doyle, C. J., R. Cousens, and S. R. Moss. 1986. A model of the economics of controlling *Alopecurus-myosuroides* Huds. in winter-wheat. Crop Protect. 5:143-150.

Dyer, W. E. 1993. Dormancy-associated embryonic mRNAs and proteins in imbibing *Avena fatua* caryopses. Physiol. Plantarum 88:201-211.

Dyer, W. E. 1995. Exploiting weed seed dormancy and germination requirements through agronomic practices. Weed Sci. 43:498-503.

Egley, G. H. 1986. Stimulation of weed seed germination in soil. Rev. Weed Sci. 2:67-89.

Egley, G. H. and J. M. Chandler. 1978. Germination and viability of weed seeds after 2.5 years in a 50 year buried seed study. Weed Sci. 230-239.

Favier, J. F. 1995. A model for germination rate during dormancy loss in *Hordeum vulgare*. Annals of Botany 76:631-638.

Fenner, M. 1985. Seed ecology. Chapman and Hall. London.

Fennimore, S. A. and M. E. Foley. 1998. Genetic and physiological evidence for the role of gibberellic acid in the germination of dormant *Avena fatua* seeds. J. Exp. Bot. 49:89-94.

Fennimore, S. A., W. E. Nyquist, G. E. Shaner, R. W. Doerge, and M. E. Foley. 1999. A genetic model and molecular markers for wild oat (*Avena fatua* L.) seed dormancy. Theor. Appl. Genet. 99:711-718.

Fennimore, S. A., W. E. Nyquist, G. E. Shaner, S. P. Myers, and M. E. Foley. 1998. Temperature response in wild oat (*Avena fatua* L.) generations segregating for seed dormancy. Heredity 81:674-682.

Fernandez-Quinantilla, C., J. L. Gonzalez Andujar, and A. P. Appleby. 1990. Characterization of the germination and emergence response to temperature and soil moisture of *Avena fatua* and *A. sterilis*. Weed Res. 30:289-295.

Figueroa, R., D. Doohan, J. Cardina, and K. Harrison. 2007. Common groundsel (*Senecio vulgaris*) seed longevity and seedling emergence. Weed Sci. 55:187-192.

Finch-Savage, W. E. and G. Leubner-Metzger. 2006. Seed dormancy and the control of germination. New Phytol. 171:501-523.

Finkelstein, R., C. Steber, T. Ariizumi, and W. Reeves. 2008. Molecular aspects of seed dormancy [electronic resource]. Annu. Rev. Plant Biol. 387-415.

Foley, M. E. 1987. The effect of wounding on primary dormancy in wild oat (*Avena fatua*) caryopses. Weed Sci. 35:180-184.

Foley, M. E. 1992. Effect of soluble sugars and gibberellic acid in breaking dormancy of excised wild oat (*Avena fatua*) embryos. Weed Sci. 40:208-214.

Foley, M. E. 1994. Temperature and water status of seed affect afterripening in wild oat (*Avena fatua*). Weed Sci. 42:200-201.

Foley, M. 2001. Seed dormancy: An update on terminology, physiological genetics, and quantitative trait loci regulating germinability. Weed Sci 49:305-317.

Forcella, F., R. L. Benech Arnold, R. Sanchez, and C. M. Ghersa. 2000. Modeling seedling emergence. Field Crops Res. 67:123-139.

Forcella, F., R. P. King, S. M. Swinton, D. D. Buhler, and J. L. Gunsolus. 1996. Multi-year validation of a decision aid for integrated weed management in row crops. Weed Sci. 44:650-661.

Forcella, F., R. G. Wilson, K. A. Renner, J. Dekker, R. G. Harvey, D. A. Alm, D. D. Buhler, and J. Cardina. 1992. Weed seedbanks of the U.S. Corn Belt: Magnitude, variation, emergence, and application. Weed Sci. 40:636-644.

Friesen, G. and L. H. Shebeski. 1961. The influence of temperature on the germination of wild oat seeds. Weeds 9:634-638.

Froud-Williams, R. J., R. J. Chancellor, and D. S. H. Drennan. 1984. The effects of seed burial and soil disturbance on emergence and survival of arable weeds in relation to minimal cultivation. J. Appl. Ecol. 21:629-641.

Gallagher R. S. and E. P. Fuerst. 2006. The Ecophysiological Basis of Weed Seed Longevity in the Soil. Pages 521-557 *In* A. S. Basra, ed. Handbook of Seed Science and Technology. Binghamton, NY: Haworth Press, Inc.

Gallandt, E. R., E. P. Fuerst, and A. C. Kennedy. 2004. Effect of tillage, fungicide seed treatment, and soil fumigation on seed bank dynamics of wild oat (*Avena fatua*). Weed Sci. 52:597-604.

Gallandt, E. R., T. Molloy, R. P. Lynch, and F. A. Drummond. 2005. Effect of cover-cropping systems on invertebrate seed predation. Weed Sci. 53:69-76.

Gan, Y., E. H. Stobbe, and J. Moes. 1992. Relative date of wheat seedling emergence and its impact on grain yield. Crop Sci. 32:1275-1281.

Gerowitt, B. and R. Heitefuss. 1990. Weed economic thresholds in cereals in the federal republic of Germany. Crop Protect. 9:323-331.

Ghersa, C. M. and M. A. Martinez-Ghersa. 2000. Ecological correlates of weed seed size and persistence in the soil under different tilling systems: Implications for weed management. Field Crops Res. 67:141-148.

Goldberg, D. E. and K. Landa. 1991. Competitive effect and response: Hierarchies and correlated traits in the early stages of competition. J. Ecol. 79:1013-1030.

Grundy, A. C. 2003. Predicting weed emergence: A review of approaches and future challenges. Weed Res. 43:1-11.

Grundy, A. C. and A. Mead. 2000. Modeling weed emergence as a function of meteorological records. Weed Sci. 48:594-603.

Gulden, R. H., S. J. Shirtliffe, and A. G. Thomas. 2003a. Harvest losses of canola (*Brassica napus*) cause large seedbank inputs. Weed Sci. 51:83-86.

Gulden, R. H., S. J. Shirtliffe, and A. G. Thomas. 2003b. Secondary seed dormancy prolongs persistence of volunteer canola in western Canada. Weed Sci. 51:904-913.

Gulden, R. H., A. G. Thomas, and S. J. Shirtliffe. 2004. Secondary dormancy, temperature, and burial depth regulate seedbank dynamics in canola. Weed Sci. 52:382-388.

Hacault, K. M. and R. C. Van Acker. 2006. Emergence timing and control of dandelion (*Taraxacum officinale*) in spring wheat. Weed Sci. 54:172-181.

Hamman, W. M. 1979. Field confirmation of an index for predicting yield loss of wheat and barley due to wild oat competition. Can. J. Plant Sci. 59:243-244.

Hanson, B. K., B. L. Johnson, R. A. Henson, and N. R. Riveland. 2008. Seeding rate, seeding depth, and cultivar influence on spring canola performance in the Northern Great Plains. Agron. J. 100:1339-1346.

Harker, K. N., R. E. Blackshaw, and G. W. Clayton. 2001. Timing weed removal in field pea (*Pisum sativum*).Weed Technol. 15:277-283.

Harker, K. N., R. E. Blackshaw, and G. W. Clayton. 2008a. Comparison of leafy and semileafless pea for integrated weed management. Weed Technol. 22:124-131.

Harker, K. N., G. W. Clayton, R. E. Blackshaw, J. T. O'Donovan, N. Z. Lupwayi, E. N. Johnson, Y. T. Gan, R. P. Zentner, G. P. Lafond, and R. B. Irvine. 2005. Glyphosate-resistant spring wheat production system effects on weed communities. Weed Sci. 53:451-464.

Harker, K. N., G. W. Clayton, R. E. Blackshaw, J. T. O'Donovan, and F. C. Stevenson. 2003a. Seeding rate, herbicide timing and competitive hybrids contribute to integrated weed management in canola (*Brassica napus*). Can. J. Plant Sci. 83:433-440.

Harker, K. N., G. W. Clayton, J. T. O'Donovan, R. E. Blackshaw and F. C. Stevenson. 2004. Herbicide timing and rate effects on weed management in three herbicide-resistant canola systems. Weed Technol.18:1006-1012.

Harker, K. N., J. T. O'Donovan, G. W. Clayton, and J. Mayko. 2008b. Field-scale time of weed removal in canola. Weed Technol. 22:747-749.

Harker, K. N., K. J. Kirkland, V. S. Baron, and G. W. Clayton. 2003b. Early-harvest barley (*Hordeum vulgare*) silage reduces wild oat (*Avena fatua*) densities under zero tillage. Weed Technol. 17:102-110.

Harker, K. N. and W. H. Vanden Born. 1997. Glyphosate or sethoxydim for quackgrass (*Elytrigia repens*) control in two tillage regimes. Weed Sci. 45:812-823.

Harman, G. E. 1983. Mechanisms of seed infection and pathogenesis. Phytopathology 73:326-329.

Harper J. L. 1977. Population biology of plants.

Harrison, S. K., E. E. Regnier, and J. T. Schmoll. 2003. Postdispersal predation of giant ragweed (*Ambrosia trifida*) seed in no-tillage corn. Weed Sci. 51:955-964.

Hilhorst H. W. M. 2007. Definitions and hypotheses of seed dormancy. Pages 50-71. *In* K. J. Bradford and H. Nonogaki, eds. Seed Development, Dormancy and Germination. Ames, Iowa: Blackwell Publishing Limited.

Hilhorst, H. W. M., A. I. Smitt, and C. M. Karssen. 1986. Gibberellin-biosynthesis and -sensitivity mediated stimulation of seed germination of *Sisymbrium officinale* by red light and nitrate. Physiol. Plantarum 67:285-290.

Hilhorst, H. W. M. and P. E. Toorop. 1997. Review on dormancy, germinability, and germination in crop and weed seeds. Adv. Agron. 111-165.

Hilton, J. R. 1984. The influence of light and potassium nitrate on the dormancy and germination of *Avena fatua* L. (Wild oat) seed and its ecological significance. New Phytol. 96:31-34.

Hilton, J. R. 1985. The influence of light and potassium nitrate on the dormancy and germination of *Avena fatua* L. (Wild oat) seed stored buried under natural conditions. J. Exp. Bot. 36:974-979.

Hilton, J. R. and C. J. Bitterli. 1983. The influence of light on the germination of *Avena fatua* L. (Wild oat) seed and its ecological significance. New Phytol. 95:325-333.

Holman, J. D., A. J. Bussan, B. D. Maxwell, P. R. Miller, and J. A. Mickelson. 2006. Persian darnel (*Lolium persicum*) fecundity response to spring wheat, canola, and sunflower interference. Weed Technol. 20:430-437.

Holmes, R. J. and R. J. Froud-Williams. 2005. Post-dispersal weed seed predation by avian and non-avian predators. Agric. Ecosyst. Environ. 105:23-27.

Honnay, O., B. Bossuyt, H. Jacquemyn, A. Shimono, and K. Uchiyama. 2008. Can a seed bank maintain the genetic variation in the above ground plant population? Oikos 117:1-5.

Hou, J. Q., E. J. Kendall, and G. M. Simpson. 1997. Water uptake and distribution in non-dormant and dormant wild oat (*Avena fatua* L.) caryopses. J. Exp. Bot. 48:683-692.

Hou, J. Q. and G. M. Simpson. 1993. Germination response to phytochrome depends on specific dormancy states in wild oat (*Avena fatua*). Can. J. Bot. 71:1528-1532.

Hsiao, A. I. H. and G. M. Simpson. 1971. Dormancy studies in seed of *Avena-fatua* .7. effects of light and variation in water regime on germination. Can. J. Bot. 49:1347-&.

Hucl, P. 1998. Response to weed control by four spring wheat genotypes differing in competitive ability. Can. J. Plant Sci. 78:171-173.

Huel, D. G. and P. Hucl. 1996. Genotypic variation for competitive ability in spring wheat. Plant Breeding 115:325-329.

Hulme, P. E. 1998. Post-dispersal seed predation: Consequences for plant demography and evolution. Perspect. Plant Ecol. Systemat. 1:32-46.

Jana, S. and J. M. Naylor. 1980. Dormancy studies in seed of *Avena fatua*. 11. Heritability for seed dormancy. Can. J. Bot. 58:91-93.

Johnson, E. N., K. J. Kirkland, and F. C. Stevenson. 2002. Timing of pre-seeding glyphosate application in direct-seeding systems. Can. J. Plant Sci. 82:611-615.

Johnson, R. R. and W. E. Dyer. 2000. Degradation of endosperm mRNAs during dry afterripening of cereal grains. Seed Sci. Res. 10:233-241.

Johnston, A. M., G. W. Clayton, G. P. Lafond, K. N. Harker, T. J. Hogg, E. N. Johnson, W. E. May, and J. T. McConnell. 2002. Field pea seeding management. Can. J. Plant Sci. 82:639-644.

Jones, R. E. and R. W. Medd. 2000. Economic thresholds and the case for longer term approaches to population management of weeds. Weed Technol. 14:337-350.

Jordan, N. 1993. Prospects for weed-control through crop interference. Ecol. Appl. 3:84-91.

Juskiw, P. E. and J. H. Helm. 2003. Barley response to seeding date in central Alberta. Can. J. Plant Sci. 83:275-281.

Kagaya, M., T. Tani, and N. Kachi. 2005. Effect of hydration and dehydration cycles on seed germination of *Aster kantoensis* (Compositae). Can. J. Bot 83:329-334.

Karssen, C. M. 1980/1981a. Environmental-conditions and endogenous mechanisms involved in secondary dormancy of seeds. Israel Journal of Botany 29:45-64.

Karssen, C. M. 1980/1981b. Patterns of change in dormancy during burial of seeds in soil. Israel Journal of Botany 29:65-73.

Karssen C. M. 1982. Seasonal patterns of dormancy in weed seeds. Pages 243-267. *In* A. A. Khan, ed. The Physiology and Biochemistry of Seed Development, Dormancy and Germination: Elsevier Biomedical Press.

Kegode, G. O., F. Forcella, and S. Clay. 1999. Influence of crop rotation, tillage, and management inputs on weed seed production. Weed Sci. 47:175-183.

Kennedy, A. C., L. F. Elliott, F. L. Young, and C. L. Douglas. 1991. Rhizobacteria suppressive to the weed downy brome. Soil Sci. Soc. Am. J. 55:722-727.

Kirkland, K. J. 1993. Spring wheat (*Triticum aestivum*) growth and yield as influenced by duration of wild oat (*Avena fatua*) competition. Weed Technol. 7:890-893.

Kirkland, K. J. and J. H. Hunter. 1991. Competitiveness of Canada Prairie spring wheats with wild oat (*Avena-fatua* L). Can. J. Plant Sci. 71:1089-1092.

Kirkland, K. J. and E. N. Johnson. 2000. Alternative seeding dates (fall and april) affect *Brassica napus* canola yield and quality. Can. J. Plant Sci. 80:713-719.

Koornneef, M., L. Bentsink, and H. Hilhorst. 2002. Seed dormancy and germination. Curr. Opin. Plant Biol. 5:33-36.

Korres, N. E. and R. J. Froud-Williams. 2002. Effects of winter wheat cultivars and seed rate on the biological characteristics of naturally occurring weed flora. Weed Res. 42:417-428.

Kremer, R. J. 1986. Antimicrobial activity of velvetleaf (*Abutilon theophrasti*) seeds. Weed Sci. 34:617-622.

Kremer, R. J. 1993. Management of weed seed banks with microorganisms. Ecol. Appl. 3:42-52.

Krupinsky, J. M., K. L. Bailey, M. P. McMullen, B. D. Gossen, and T. K. Turkington. 2002. Managing plant disease risk in diversified cropping systems. Agron. J. 94:198-209.

Lafond, G. P., S. M. Boyetchko, S. A. Brandt, G. W. Clayton, and M. H. Entz. 1996. Influence of changing tillage practices on crop production. Can. J. Plant Sci. 76:641-649.

Lawson, A. N., L. F. Friesen, and R. C. Van Acker. 2006. Emergence timing of volunteer canola in spring wheat fields in Manitoba. Weed Sci. 54:873-882.

Leeson J. Y. 2002. 2002 Manitoba Alberta weed survey of cereal, oilseed, and pulse crops. Saskatoon, SK: Agriculture and Agri-Food Canada Weed Survey Series Publ. 02-2. 141 p.

Leeson, J. Y., A. G. Thomas, and C. Bremzil. 2003. 2003 Saskatchewan weed survey of cereal, oilseed, and pulse crops. Saskatoon, SK: Agriculture and Agri-Food Canada Weed Survey Series Publ. 03-1. 342 p.

Leeson, J. Y., A. G. Thomas, and L. M. Hall. 2002. 2001 Alberta weed survey of cereal, oilseed, and pulse crops. Saskatoon, SK: Agriculture and Agri-Food Canada Weed Survey Series Publ. 02-1. 263 p.

Leeson J. Y., A. G. Thomas, and J. T. O'Donovan. 2006. Economic impact of alien weeds on wheat, barley and canola production. Proc. Canadian Weed Sci. Soc. , Nov. 27-29. Victoria, BC .

Legere, A. and E. C. Stevenson. 2002. Residual effects of crop rotation and weed management on a wheat test crop and weeds. Weed Sci. 50:101-111.

Lemerle, D., B. Verbeek, R. D. Cousens, and N. E. Coombes. 1996. The potential for selecting wheat varieties strongly competitive against weeds. Weed Res. 36:505-513.

Levin, D. A. 1990. The seed bank as a source of genetic novelty in plants. Am. Nat. 135:563-572.

Li, B. and M. E. Foley. 1994. Differential polypeptide patterns in imbibed dormant and after-ripened *Avena fatua* embryos. J. Exp. Bot. 45:275-279.

Li, B. and M. E. Foley. 1995. Cloning and characterization of differentially expressed genes in imbibed dormant and afterripened *Avena fatua* embryos. Plant Mol. Biol. 29:823-831.

Li, B. and M. E. Foley. 1996. Transcriptional and posttranscriptional regulation of dormancy-associated gene expression by afterripening in wild oat. Plant Physiology 110:1267-1273.

Li, B. and M. Foley. 1997. Genetic and molecular control of seed dormancy. Trends Plant Sci. 2:384-389.

Li, W., X. Liu, M. A. Khan, Y. Kamiya, and S. Yamaguchi. 2005. Hormonal and environmental regulation of seed germination in flixweed (*Descurainia sophia*). Plant Growth Regul. 45:199-207.

Liebman, M. and A. S. Davis. 2000. Integration of soil, crop and weed management in low-external-input farming systems. Weed Res. 40:27-47.

Liebman, M. and E. Dyck. 1993. Crop rotation and intercropping strategies for weed management. Ecol. Appl. 3:92-122.

Liu, G., L. Luo, B. Wang, W. Li, and Z. Song. 2006. Comparison of genetic variation in populations of wild rice, *Oryza rufipogon*, plants and their soil seed banks. Conservat. Genet. 7:909-917.

Lutman, P. J. W. 2002. Estimation of seed production by *Stellaria media*, *Sinapis arvensis* and *Tripleurospermum inodorum* in arable crops. Weed Res. 42:359-369.

Mahy, G., X. Vekemans, and A. L. Jacquemart. 1999. Patterns of allozymic variation within *Calluna vulgaris* populations at seed bank and adult stages. Heredity 82:432-440.

Malhi, S. S., C. A. Grant, A. M. Johnston, and K. S. Gill. 2001. Nitrogen fertilization management for no-till cereal production in the Canadian Great Plains: A review. Soil Tillage Res. 60:101-122.

Malhi, S. S., E. Oliver, G. Mayerle, G. Kruger, and K. S. Gill. 2003. Improving effectiveness of seedrow-placed urea with urease inhibitor and polymer coating for durum wheat and canola. Commun. Soil Sci. Plant Anal. 34:1709-1727.

Mandák, B., K. Bímová, V. Mahelka, and I. Plačková. 2006. How much genetic variation is stored in the seed bank? A study of *Atriplex tatarica* (Chenopodiaceae) [electronic resource]. Mol. Ecol. 15:2653-2663.

Marino, P. C., K. L. Gross, and D. A. Landis. 1997. Weed seed loss due to predation in Michigan maize fields. Agric. Ecosyst. Environ. 66:189-196.

Marino, P. C., P. R. Westerman, C. Pinkert, and W. van der Werf. 2005. Influence of seed density and aggregation on post-dispersal weed seed predation in cereal fields. Agric. Ecosyst. Environ 106:17-25.

Martinkova, Z., A. Honek, and J. Lukas. 2006. Seed age and storage conditions influence germination of barnyardgrass (*Echinochloa crus-galli*). Weed Sci. 54:298-304.

Martinson, K., K. Spokas, D. Archer, J. Wiersma, B. Durgan, and F. Forcella. 2007. An emergence model for wild oat (*Avena fatua*). Weed Sci. 55:584-591.

Masin, R., M. C. Zuin, S. Otto, and G. Zanin. 2006. Seed longevity and dormancy of four summer annual grass weeds in turf. Weed Res. 46:362-370.

Mason, H., A. Navabi, B. Frick, J. O'Donovan, and D. Spaner. 2007. Cultivar and seeding rate effects on the competitive ability of spring cereals grown under organic production in northern Canada . Agron. J. 99:1199-1207.

Matilla, A., M. Gallardo, and M. I. Puga-Hermida. 2005. Structural, physiological and molecular aspects of heterogeneity in seeds: A review. Seed Sci. Res. 15:63-76.

Mauchline A. L., S. J. Watson, V. K. Brown, and R. J. Froud Williams. 2005. Post-dispersal seed predation of non-target weeds in arable crops. Weed Res. 45:157-164.

May, W. E., R. M. Mohr, G. P. Lafond, A. M. Johnston, and F. C. Stevenson. 2004. Early seeding-dates improve oat yield and quality in the eastern Prairies. Can. J. Plant Sci. 84:431-442.

McDonald, M. B. 1999. Seed deterioration: Physiology, repair and assessment. Seed Sci. & Technol. 27:177-237.

McKenzie, R. H., A. B. Middleton, and E. Bremer. 2005. Fertilization, seeding date, and seeding rate for malting barley yield and quality in southern Alberta. Can. J. Plant Sci. 85:603-614.

Menalled F. D., M. Liebman, and K. A. Renner. 2006. The ecology of weed seed predation in herbaceous crop systems. Pages 297-327. *In* Singh H.P., Batish D.R. and Kohli R.K., eds. Handbook of sustainable weed management: Binghamton, USA: Food Products Press.

Menalled, F. D., P. C. Marino, K. A. Renner, and D. A. Landis. 2000. Post-dispersal weed seed predation in Michigan crop fields as a function of agricultural landscape structure. Agric. Ecosyst. Environ. 77:193-202.

Menalled, F. D., R. G. Smith, J. T. Dauer, and T. B. Fox. 2007. Impact of agricultural management on carabid communities and weed seed predation. Agric. Ecosyst. Environ .118:49-54.

Metzger, J. D. 1983. Role of endogenous plant growth regulators in seed dormancy of *Avena fatua*. Plant Physiol. 73:791-795.

Mickelson, J. A. and W. E. Grey. 2006. Effect of soil water content on wild oat (*Avena fatua*) seed mortality and seedling emergence. Weed Sci. 54:255-262.

Milberg, P. and L. Andersson. 1998. Does cold stratification level out differences in seed germinability between populations? Plant Ecol. 134:225-234.

Miller, S. D. and J. D. Nalewaja. 1990. Influence of burial depth on wild oats (*Avena fatua*) seed longevity. Weed Technol. 4:514-517.

Mohamed-Yasseen, Y., S. A. Barringer, W. E. Splittstoesser, and S. Costanza. 1994. The role of seed coats in seed viability. Bot. Rev. 60:426-439.

Monks, C. D., D. C. Bridges, J. W. Woodruff, T. R. Murphy, and D. J. Berry. 1995. Expert system evaluation and implementation for soybean (*Glycine max*) weed management. Weed Technol. 9:535-540.

Morishita, D. W. and D. C. Thill. 1988. Factors of wild oat (*Avena fatua*) interference on spring barley (*Hordeum vulgare*) growth and yield. Weed Sci. 36:37-42.

Morris, A. B., R. S. Baucom, and M. B. Cruzan. 2002. Stratified analysis of the soil seed bank in the cedar glade endemic *Astragalus bibullatus*: Evidence for historical changes in genetic structure. Am. J. Bot. 89:29-36.

Mostaghimi, S., T. M. Younos, and U. S. Tim. 1992. Crop residue effects on nitrogen yield in water and sediment runoff from two tillage systems. Agric. Ecosyst. Environ. 39:187-196.

Mt Pleasant, J. and K. J. Schlather. 1994. Incidence of weed seed in cow (*Bos* sp.) manure and its importance as a weed source for cropland. Weed Technol. 8:304-310.

Murphy, S. D., D. R. Clements, S. Belaoussoff, P. G. Kevan, and C. J. Swanton. 2006. Promotion of weed species diversity and reduction of weed seedbanks with conservation tillage and crop rotation. Weed Sci. 54:69-77.

Myers, S. P., M. E. Foley, and M. B. Nichols. 1997. Developmental differences between germinating after-ripened and dormant excised *Avena fatua* L. embryos. Annals of Botany 79:19-23.

Nonogaki H., F. Chen, and K. J. Bradford. 2007. Mechanisms and genes involved in germination *sensu stricto*. Pages 265-304 *In* K. J. Bradford and H. Nonogaki, eds. Seed Development, Dormancy and Germination. Ames, Iowa: Blackwell Publishing Limited.

Norris, R. F. 2007. Weed fecundity: Current status and future needs. Crop Protect. 26:182-188.

Norsworthy, J. K. and M. J. Oliveira. 2007. Tillage and soybean canopy effects on common cocklebur (*Xanthium strumarium*) emergence [electronic resource]. Weed Sci. 55:474-480.

Nunney, L. 2002. The effective size of annual plant populations: The interaction of a seed bank with fluctuating population size in maintaining genetic variation. The American Naturalist 160:195-204.

O'Donovan, J. T. 1996. Computerised decision support systems: Aids to rational and sustainable weed management. Can. J. Plant Sci. 76:3-7.

O'Donovan, J. T., R. E. Blackshaw, K. N. Harker, and G. W. Clayton. 2006. Wheat seeding rate influences herbicide performance in wild oat (*Avena fatua* L.) [electronic resource]. Agron. J. 98:815-822.

O'Donovan, J. T., R. E. Blackshaw, K. N. Harker, G. W. Clayton, and D. C. Maurice. 2005a. Field evaluation of regression equations to estimate crop yield losses due to weeds. Can. J. Plant Sci. 85:955-962.

O'Donovan, J. T., R. E. Blackshaw, K. N. Harker, G. W. Clayton, and R. McKenzie. 2005b. Variable crop plant establishment contributes to differences in competitiveness with wild oat among cereal varieties. Can. J. Plant Sci. 85:771-776.

O'Donovan, J. T., R. E. Blackshaw, K. N. Harker, G. W. Clayton, J. R. Moyer, L. M. Dosdall, D. C. Maurice, and T. K. Turkington. 2007. Integrated approaches to managing weeds in spring-sown crops in western Canada. Crop Protect. 26:390-398.

O'Donovan, J. T., E. A. De St Remy, P. A. O'Sullivan, D. A. Dew, and A. K. Sharma. 1985. Influence of the relative time of emergence of wild oat (*Avena fatua*) on yield loss of barley (*Hordeum vulgare*) and wheat (*Triticum aestivum*). Weed Sci. 33:498-503.

O'Donovan, J. T., K. N. Harker, G. W. Clayton, and R. E. Blackshaw. 2006. Comparison of a glyphosate-resistant canola (*Brassica napus* L.) system with traditional herbicide regimes. Weed Technol. 20:494-501.

O'Donovan, J. T., K. N. Harker, G. W. Clayton, and L. M. Hall. 2000. Wild oat (*Avena fatua*) interference in barley (*Hordeum vulgare*) is influenced by barley variety and seeding rate. Weed Technol. 14:624-629.

O'Donovan, J. T., K. N. Harker, G. W. Clayton, L. M. Hall, J. Cathcart, K. L. Sapsford, F. A. Holm, and K. Hacault. 2007. Volunteer barley interference in spring wheat grown in a zero-tillage system. Weed Sci. 55:70-74.

O'Donovan, J. T., K. N. Harker, G. W. Clayton, J. C. Newman, D. Robinson, and L. M. Hall. 2001. Barley seeding rate influences the effects of variable herbicide rates on wild oat. Weed Sci. 49:746-754.

O'Donovan, J. T., J. C. Newman, R. E. Blackshaw, K. N. Harker, D. A. Derksen, and A. G. Thomas. 1999a. Growth, competitiveness, and seed germination of triallate/difenzpquat-susceptible and -resistant wild oat populations. Can. J. Plant Sci. 79:303-312.

O'Donovan, J. T., J. C. Newman, K. N. Harker, R. E. Blackshaw, and D. W. McAndrew. 1999b. Effect of barley plant density on wild oat interference, shoot biomass and seed yield under zero tillage. Can. J. Plant Sci. 79:655-662.

O'Donovan, J. T., J. C. Newman, K. N. Harker, and G. W. Clayton. 2004. Crop seeding rate influences the performance of variable herbicide rates in a canola-barley-canola rotation. Weed Technol. 18:733-741.

O'Donovan, J. T., T. K. Turkington, N. Z. Lupwayi, K. N. Harker, G. W. Clayton, and C. A. Grant. 2008. Effect of nitrogen rate and placement and seeding rate on barley productivity and wild oat fecundity in a zero tillage system. Crop Sci. 48:1569-1574.

Olfert, O. and R. M. Weiss. 2002. Impact of grasshopper feeding on selected cultivars of cruciferous oilseed crops. J. Orthopt. Res. 11:83-86.

Ominski, P. D., M. H. Entz, and N. Kenkel. 1999. Weed suppression by *Medicago sativa* in subsequent cereal crops: A comparative survey. Weed Sci. 47:282-290.

O'Rourke, M. E., A. H. Heggenstaller, M. Liebman, and M. E. Rice. 2006. Post-dispersal weed seed predation by invertebrates in conventional and low-external-input crop rotation systems. Agric. Ecosyst. Environ. 116:280-288.

Page, E. R., A. R. Kemanian, E. P. Fuerst, and R. S. Gallagher. 2007. Spatially variable patterns of wild oat emergence in eastern Washington [electronic resource]. Crop Protection 26:232-236.

Page, E. R., H. Zhang, E. P. Fuerst, R. S. Gallagher, and A. R. Kemanian. 2006. Modeling site-specific wild oat (*Avena fatua*) emergence across a variable landscape. Weed Sci. 54:838-846.

Pareja, M. R. and D. W. Staniforth. 1985. Seed-soil microsite characteristics in relation to weed seed germination. Weed Sci. 33:190-195.

Peters, N. C. B. 1982. The dormancy of wild oat seed (*Avena fatua* L.) from plants grown under various temperature and soil moisture conditions. Weed Res. 22:205-212.

Pitty, A., D. W. Staniforth, and L. H. Tiffany. 1987. Fungi associated with caryopses of *Setaria* species from field-harvested seeds and from soil under two tillage systems. Weed Sci. 35:319-323.

Prasifka, J. R., N. P. Schmidt, K. A. Kohler, M. E. O'Neal, R. L. Hellmich, and J. W. Singer. 2006. Effects of living mulches on predator abundance and sentinel prey in a corn-soybean-forage rotation. Environ. Entomol. 35:1423-1431.

Priestley D. A. 1986. Seed Aging: Implications for Seed Storage and Persistence in the Soil. . Ithaca, NY: Comstock Publishing Associates. 304 p.

Probert R. J. 2000. The role of temperature in the regulation of seed dormancy and germination. Pages 261-292 *In* M. Fenner, ed. Seeds: The Ecology of Regeneration in Plant Communities. 2nd ed. Wallingford, UK: CABI Publishing.

Riemens M. M., P. C. Scheepens, and R. Y. v. d. Weide. 2004. Dormancy, Germination and Emergence of Weed Seeds, with Emphasis on the Influence of Light: Results of a Literature Survey. Wageningen: Plant Research International. Pp. 26 plus appendix.

Roberts, H. A. 1964. Emergence and longevity in cultivated soil of seeds of some annual weeds. Weed Res. 4:296-307.

Roberts, H. A. 1981. Seed banks in soils. Adv. Appl. Biol. 1-55.

Roman, E., S. D. Murphy, and C. J. Swanton. 2000. Simulation of *Chenopodium album* seedling emergence. Weed Sci. 48:217-224.

Roman, E., A. G. Thomas, S. D. Murphy, and C. J. Swanton. 1999. Modeling germination and seedling elongation of common lambsquarters (*Chenopodium album*). Weed Sci 47:149-155.

Sawhney, R. and J. M. Naylor. 1979. Dormancy studies in a seed of *Avena fatua*. 9. Demonstration of genetic variability affecting the response to temperature during seed development. Can. J. Bot. 57:59-63.

Sawhney, R. and J. M. Naylor. 1980. Dormancy studies in seed of *Avena fatua*. 12. Influence of temperature on germination behavior of nondormant families. Can. J. Bot. 58:578-581.

Sawhney, R. and J. M. Naylor. 1982. Dormancy studies in seed of *Avena fatua*. 13. Influence of drought stress during seed development on duration of seed dormancy. Can. J. Bot. 60:1016-1020.

Schoenau, J. J. and C. A. Campbell. 1996. Impact of crop residues on nutrient availability in conservation tillage systems. Can. J. Plant Sci. 76:621-626.

Schreiber, M. M. 1992. Influence of tillage, crop rotation, and weed management on giant foxtail (*Setaria faberi*) population dynamics and corn yield. Weed Sci. 40:645-653.

Schutte, B. J., J. Cardina, K. A. Renner, and A. S. Davis. 2008. Maternal and burial environment effects on seed mortality of velvetleaf (*Abutilon theophrasti*) and giant foxtail (*Setaria faberi*). Weed Sci. 56:834-840.

Schweizer, E. E. and R. L. Zimdahl. 1984. Weed seed decline in irrigated soil after six years of continuous corn *(Zea mays*) and herbicides. Weed Sci. 32:76-83.

Schwinghamer, T. D. and R. C. Van Acker. 2008. Emergence timing and persistence of kochia (*Kochia scoparia*) [electronic resource]. Weed Sci. 56:37-41.

Scursoni, J. A. and E. H. Satorre. 2005. Barley (*Hordeum vulgare*) and wild oat (*Avena fatua*) competition is affected by crop and weed density. Weed Technol. 19:790-795.

Sharma, M. P., D. K. McBeath, and W. H. Vanden-Born. 1976. Studies on the biology of wild oats. I. Dormancy, germination and emergence. Can. J. Plant Sci. 611-618.

Sharma, M. P. and W. H. Vanden Born. 1978. The biology of Canadian weeds. 27. *Avena fatua* L. Can. J. Plant Sci.141-157.

Shirtliffe, S. J. and M. H. Entz. 2005. Chaff collection reduces seed dispersal of wild oat (*Avena fatua*) by a combine harvester. Weed Sci. 53:465-470.

Shirtliffe, S. J., M. H. Entz, and R. C. Van Acker. 2000. *Avena fatua* development and seed shatter as related to thermal time. Weed Sci. 48:555-560.

Simpson G. M. 1990. Seed dormancy in grasses. Cambridge, England : Cambridge University Press. 297 p.

Simpson R. L., M. A. Leck, and V. T. Parker. 1989. Seed banks: general concepts and methodological issues. Pages 3-8 *In* M. A. Leck, V. T. Parker and R. L. Simpson, eds. Ecology of Soil Seed Banks. San Diego, California, U.S.A.: Academic Press, Inc.

Śliwińska, E. and E. Jendrzejczak. 2002. Sugar-beet seed quality and DNA synthesis in the embryo in relation to hydration-dehydration cycles. Seed Sci. Technol. 30:597-608.

Sosnoskie, L. M., C. P. Herms, and J. Cardina. 2006. Weed seedbank community composition in a 35-yr-old tillage and rotation experiment. Weed Sci. 54:263-273.

Spandl, E., B. R. Durgan, and F. Forcella. 1998. Tillage and planting date influence foxtail (*Setaria spp*.) emergence in continuous spring wheat (*triticum aestivum*). Weed Technol. 12:223-229.

Statistics Canada. 2008. Conventional tillage: How conventional is it? EnviroStats 2:13-15.

Swanton, C. J., B. D. Booth, K. Chandler, D. R. Clements, and A. Shrestha. 2006. Management in a modified no-tillage corn-soybean-wheat rotation influences weed population and community dynamics. Weed Sci. 54:47-58.

Telewski, F. W. and J. A. D. Zeevaart. 2002. The 120-yr period for Dr. Beal's seed viability experiment. Am. J. Bot. 89:1285-1288.

Templeton, A. R. and D. A. Levin. 1979. Evolutionary consequences of seed pools. Am. Nat. 114:232-249.

Tessier, S., M. Peru, F. B. Dyck, R. P. Zentner, and C. A. Campbell. 1990. Conservation tillage for spring wheat in semi-arid Saskatchewan. Soil Tillage Res. 18:73-89.

Thomas, A. G., D. A. Derksen, R. E. Blackshaw, R. C. Van Acker, A. Legere, P. R. Watson, and G. C. Turnbull. 2004. A multistudy approach to understanding weed population shifts in medium- to long-term tillage systems. Weed Sci. 52:874-880.

Thompson, C. R., B. K. Hoag, and J. R. Lukach. 1988. Flax variety response to planting date. N. D. Farm Res. 45:22-26.

Thompson, K. 1987. Seeds and seed banks. New Phytol. (Suppl.) 106:23-34.

Thompson K., Band S.R., Hodgson J.G. 1993. Seed size and shape predict persistence in soil. Funct. Ecol. 7:236-241.

Thompson, K., J. P. Bakker, R. M. Bekker, and J. G. Hodgson. 1998. Ecological correlates of seed persistence in soil in the north-west European flora. J. Ecol. 86:163-169.

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

Thurston, J. M. 1961. The effect of depth of burying and frequency of cultivation on survival and germination of seeds of wild oats (*Avena fatua* L. and *Avena ludoviciana* Dur.). Weed Res. 1:19-31.

Tonsor, S. J., S. Kalisz, J. Fisher, and T. P. Holtsford. 1993. A life-history based study of population genetic structure: Seed bank to adults in *Plantago lanceolata*. Evolution 47:833-843.

Toole, E. H. and E. Brown. 1946. Final results of the Duvel buried seed experiment. J. Ag. Res. 72:201-210.

Upadhyaya, M. K., J. M. Naylor, and G. M. Simpson. 1982. The physiological basis of seed dormancy in *Avena fatua* L. I. Action of the respiratory inhibitors sodium azide and salicylhydroxamic acid. Physiol. Plantarum 54:419-424.

Upadhyaya, M. K., J. M. Naylor, and G. M. Simpson. 1983. The physiological basis of seed dormancy in *Avena fatua*. II. On the involvement of alternative respiration in the stimulation of germination by sodium azide. Physiol. Plantarum 58:119-123.

Van Acker, R. C., W. J. Bullied, and M. J. Du Croix Sissons. 2004. Tillage index predicts weed seedling recruitment depth. Can. J. Plant Sci. 84:319-326.

Van Delden, A., L. A. P. Lotz, L. Bastiaans, A. C. Franke, H. G. Smid, R. M. W. Groeneveld, and M. J. Kropff. 2002. The influence of nitrogen supply on the ability of wheat and potato to suppress *Stellaria media* growth and reproduction. Weed Res. 42:429-445.

Van Mourik, T. A., T. J. Stomph, and A. J. Murdoch. 2005. Why high seed densities within buried mesh bags may overestimate depletion rates of soil seed banks. J. Appl. Ecol. 42:299-305.

Vegis, A. 1964. Dormancy in higher plants. Annu. Rev. Plant Physiol.15:185-&.

Venable, D. L. and J. S. Brown. 1988. The selective interactions of disperal, dormancy, and seed size as adaptations for reducing risk in variable environments. Am. Nat. 131:360-384.

Vengris, J., M. Drake, W. G. Colby, and J. Bart. 1953. Chemical composition of weeds and accompanying crop plants. Agron. J. 45:213-218.

Vitalis, R., S. Glemin, and I. Olivieri. 2004. When genes go to sleep: The population genetic consequences of seed dormancy and monocarpic perenniality. Am. Nat. 163:295-311.

Vleeshouwers, L. M., H. J. Bouwmeester, and C. M. Karssen. 1995. Redefining seed dormancy: An attempt to integrate physiology and ecology. J. Ecol. 83:1031-1037.

Wagner, M. and N. Mitschunas. 2008. Fungal effects on seed bank persistence and potential applications in weed biocontrol: A review. Basic Appl. Ecol. 9:191-203.

Watanabe, H., Y. Kusagaya, and M. Saigusa. 2002. Environmental factors affecting germination of apple of Peru. Weed Sci. 50:152-156.

Watson, P. R., D. A. Derksen, and R. C. Van Acker. 2006. The ability of 29 barley cultivars to compete and withstand competition. Weed Sci. 54:783-792.

Westerman, P. R., A. Hofman, L. E. M. Vet, and W. van der Werf. 2003a. Relative importance of vertebrates and invertebrates in epigeaic weed seed predation in organic cereal fields. Agric. Ecosyst. Environ. 95:417-425.

Westerman, P. R., J. S. Wes, M. J. Kropff, and W. Van der Werf. 2003b. Annual losses of weed seeds due to predation in organic cereal fields. J. Appl. Ecol. 40:824-836.

White, N. D. G., R. B. Hulasare, and D. S. Jayas. 1999. Effects of storage conditions on quality loss of hull-less and hulled oats and barley. Can. J. Plant Sci. 79:475-482.

White, S. S., K. A. Renner, F. D. Menalled, and D. A. Landis. 2007. Feeding preferences of weed seed predators and effect on weed emergence. Weed Sci. 55:606-612.

Wicks, G. A., R. E. Ramsel, P. T. Nordquist, J. W. Schmidt, and Challaiah. 1986. Impact of wheat cultivars on establishment and suppression of summer annual weeds. Agron. J. 78:59-62.

Wiles, L. J., H. J. Gold, and G. G. Wilkerson. 1993. Modeling the uncertainty of weed density estimates to improve postemergence herbicide control decisions. Weed Res. 33:241-252.

Wilkerson, G. G., S. A. Modena, and H. D. Coble. 1991. HERB: Decision model for postemergence weed control in soybean. Agron. J. 83:413-417.

Wilkerson, G. G., L. J. Wiles, and A. C. Bennett. 2002. Weed management decision models: Pitfalls, perceptions, and possibilities of the economic threshold approach. Weed Sci. 50:411-424.

Willenborg, C. J., G. P. Lafond, S. J. Shirtliffe, W. E. May, and R. H. Gulden. 2005a. Influence of wild oat (*Avena fatua*) relative time of emergence and density on cultivated oat field, wild oat seed production, and wild oat contamination. Weed Sci. 53:342-352.

Willenborg, C. J., B. G. Rossnagel, W. E. May, G. P. Lafond, and S. J. Shirtliffe. 2005b. Effects of relative time of emergence and density of wild oat (*Avena fatua* L.) on oat quality. Can. J. Plant Sci.:561-567.

Xue, Q. W. and R. N. Stougaard. 2002. Spring wheat seed size and seeding rate affect wild oat demographics. Weed Sci. 50:312-320.

Yenish, J. P., T. A. Fry, B. R. Durgan, and D. L. Wyse. 1996. Tillage effects on seed distribution and common milkweed (*Asclepias syriaca*) establishment. Weed Sci. 44:815-820.

Zand, E. and H. J. Beckie. 2002. Competitive ability of hybrid and open-pollinated canola (*Brassica napus*) with wild oat (*Avena fatua*). Can. J. Plant Sci. 82:473-480.

Zentner, R. P., S. A. Brandt, K. J. Kirkland, C. A. Campbell, and G. J. Sonntag. 1992. Economics of rotation and tillage systems for the dark brown soil zone of the Canadian Prairies. Soil Tillage Res. 24:271-284.

Zentner, R. P., G. P. Lafond, D. A. Derksen, and C. A. Campbell. 2002a. Tillage method and crop diversification: Effect on economic returns and riskiness of cropping systems in a thin black chernozem of the Canadian Prairies. Soil Tillage Res. 67:9-21.

Zentner, R. P., D. D. Wall, C. C. Nagy, E. G. Smith, D. L. Young, P. R. Miller, C. A. Campbell, B. G. McConkey, S. A. Brandt, G. P. Lafond, A. M. Johnston, and D. A. Derksen. 2002b. Economics of crop diversification and soil tillage opportunities in the Canadian Prairies. Agron. J. 94:216-230.

Zhang J., F. A. Drummond, M. Liebman, and A. Hartke. 1997. Insect predation of seeds and plant population dynamics. Orono, ME: Maine Agricultural and Forest Experiment Station. 28 p.

Chapter 3. The Effects of Crop Rotation, Barley Cultivar, Barley Seeding Rate and Herbicide Rate on Wild Oat (*Avena fatua* L.) Seed Bank Density and Seed Mortality

3.1. Introduction

An interest in integrated weed management (IWM) from western Canadian producers continues to grow with increasing costs of fertilizers, herbicides and seed. Concerns about herbicide-resistant weeds, the residual effects of herbicides on crops and the environment as well as concerns of pesticides on human health are some reasons explaining a demand for alternative cropping practices (Beckie et al. 2008c; Blackshaw et al. 2008; O'Donovan et al. 2007a). To address the complex nature of economic, environmental and social concerns within weed management, an integrated systems approach is required (Swanton and Murphy 1996; Swanton et al. 2008). The primary goal of IWM research is to determine the best combination of agronomic practices that enhance crop competitiveness and reduce herbicide use while providing long-term weed control, within an economical, environmental and sociological sustainable system.

Achieving this goal requires integrating agronomy, weed biology and weed ecology research. Integrated approaches to weed management have included the use of direct seeding (Murphy et al. 2006), increased seeding rates (Harker et al. 2003; O'Donovan et al. 2001; O'Donovan et al. 2004; O'Donovan et al. 2008), competitive crop cultivars (Harker et al. 2003; Harker et al. 2008; O'Donovan et al. 2005; Watson et al. 2006) and diverse crop rotations (Blackshaw et al. 2005a;

Blackshaw et al. 2005b). Integrating agronomic practices with early weed removal (Harker et al. 2001; Harker et al. 2003; Harker et al. 2004; Martin et al. 2001) and judicious rates of herbicides (O'Donovan et al. 2001; O'Donovan et al. 2006) can be used to increase seedling mortality, reduce weed densities and minimize seed production (Blackshaw et al. 2008; Norris 2007; Swanton and Booth 2004), thus reducing the capacity for the seed bank to buffer weed communities (Buhler et al. 2000).

Seed banks are composed of cohorts of viable seeds found in or on the soil surface (Cavers 1995; Simpson et al. 1989) that act as a source of important genetic variation (Levin 1990). Changes in species composition and density are a product of both weed management (Cardina et al. 2002; Clements et al. 1996; Murphy et al. 2006; Sosnoskie et al. 2006; Swanton et al. 2006) and environmental conditions (Davis et al. 2005). Weed seeds are added to the seed bank predominantly during crop growth through seed rain but may enter with machinery, contaminated crop seeds, animals, wind, water, and manure (Buhler et al. 1997). Many weed species are prolific seed producers, with the ability to produce hundreds to millions of seeds, depending on species and density of crop and weed as well as, management practices (Norris 2007). As a result, under conditions of favourable weed growth or unsatisfactory management, weed escapes replenish seed banks, maintaining or augmenting populations over time (Belles et al. 2000; Gallandt 2006; Martinson et al. 2007; Schweizer and Zimdahl 1984). Reducing or eliminating seed production can reduce the number of seeds entering the seed bank. Burnside et al. (1986) reported seed bank declines up to

95% over 5 years when seed production was eliminated; however, discontinuing management practices for one year replenished seed banks to 90% of original populations. Although reducing fecundity is effective in depleting the seed bank over time, some weed species produce seeds that persist in the soil for many years.

Upon entering the seed bank, seeds can remain on the soil surface or become buried in the soil profile. Seeds within the seed bank can germinate if environmental conditions are favourable; however, dormant seeds do not germinate but persist. Persistent seed banks contain seeds that can remain viable and germinate over two or more years (Burnside et al. 1996; Conn and Farris 1987; Conn and Deck 1995; Conn et al. 2006; Lutman et al. 2002). Seed longevity studies indicate that many weed species can persist in the soil for decades (Telewski and Zeevaart 2002; Toole and Brown 1946). Seed bank persistence is a function of soil disturbance (Thompson et al. 1998), seed burial (Bekker et al. 1998; Thompson et al. 1998), primary and secondary dormancy (Benech-Arnold et al. 2000), post-dispersal seed predation (Cromar et al. 1999; Harrison et al. 2003; Menalled et al. 2007) and resistance to soil microorganisms (Chee-Sanford et al. 2006; Kremer 1986; Kremer 1993). For many annual weed species, persistence is influenced largely by the degree of dormancy and dormancy cycling (Benech-Arnold et al. 2000). Relief from primary dormancy and the induction of secondary dormancy followed by subsequent cycles of secondary dormancy permit a proportion of weed seedlings to emerge in a given year (Baskin and Baskin 1998). Changes in soil temperature and soil moisture influence the dormancy status of weed seeds (Batlla et al. 2004; Batlla and Benech-Arnold 2007). Termination of dormancy, through exposure to specific environmental conditions such as fluctuating temperatures, light, carbon dioxide, nitrate, oxygen and ethylene may occur once a low level of dormancy is achieved (Benech-Arnold et al. 2000). The termination of dormancy followed by favourable environmental conditions will permit germination and seedling emergence. As a result, the interaction of dormancy levels in the weed seed bank and environmental variables influencing germination make it difficult to predict seedling density (Batlla and Benech-Arnold 2007; Benech-Arnold et al. 2000; Forcella et al. 2000).

Predicting seedling emergence from the soil seed bank can improve implementation of weed control measures (Buhler et al. 1997); however, the relationship between seedling recruitment and soil seed bank can exhibit a large degree of variability across weed species. Zhang et al. (1998) found the relationship between soil seed bank and seedling recruitment for giant foxtail, [*Setaria faberi* Herrm.], green foxtail [*Setaria virdis* (L.) Beauv.] and yellow foxtail [*Setaria* (Poir.) Roem & Schult] to be highly correlated (R^2 = 0.80 to 0.88), but for common lambsquarters (*Chenopodium album* L.) the correlations were more variable (R^2 = 0.25 to 0.44). Incorporating additional weed growth parameters such as seed rain with seed bank density may be used to improve estimations of weed seedling recruitment (Webster et al. 2003). Understanding factors that influence seed bank persistence and regulate weed emergence will improve implementation of IWM strategies.

Seeds can be removed from the soil seed bank through physiological and microbial decay, exhaustion, physical movement and predation (Buhler et al. 1997). Weed seeds on or near the soil surface are more prone to seed predation and decay than buried seeds. Significant removal of seeds from the soil surface has been reported through post dispersal seed predation (Cromar et al. 1999; Davis and Liebman 2003; Gallandt et al. 2005; Jacob et al. 2006; Mauchline et al. 2005; Menalled et al. 2000; Menalled et al. 2007; O'Rourke et al. 2006; Westerman et al. 2003a; Westerman et al. 2003b), but this mechanism has not yet been characterized for western Canada. Several factors influence the amount of seed predation in arable habitats, including the type of predator (vertebrate or invertebrate) (Cromar et al. 1999; Holmes and Froud-Williams 2005; Marino et al. 1997), feeding preferences (White et al. 2007), seed aggregation (Marino et al. 2005), environmental factors (Zhang et al. 1997), plant phenology and physiology (Harrison et al. 2003; Hulme 1998), and management practices (Cromar et al. 1999; Davis and Liebman 2003; Gallandt et al. 2005; Mauchline et al. 2005; Menalled et al. 2000; O'Rourke et al. 2006; Westerman et al. 2003a; Westerman et al. 2003b). Nevertheless, very few studies have identified the implications or magnitude of weed seed losses within western Canadian cropping systems.

Artificial seed banks have been frequently used to study seed bank dynamics, including germination (Bello et al. 1998; Burnside et al. 1996; Gallagher and Cardina 1998), decay (Mitschunas et al. 2006; Van Mourik et al. 2005), predation (Harrison et al. 2003; Menalled et al. 2000; Westerman et al. 2003a) and seedling emergence (Benvenuti et al. 2001). Seed bag burial is a practical method to study the longevity and dormancy of a cohort of seeds in the seed bank (Egley and Chandler 1978; Lewis 1973); however, this method can potentially overestimate seed bank depletion (Van Mourik et al. 2005) and seed longevity (Masin et al. 2006). For instance, soil disturbances that occur during the placement of seed bags can alter soil bulk density and soil temperature resulting in different levels of seed bank depletion and seedling emergence than in a natural seed bank (Leon and Owen 2004). Natural seed banks are more difficult to study since the size, composition and seed depth are highly variable in space and time (Benvenuti 2007). Nevertheless, natural seed banks have the potential to reflect seed bank depletions and seed longevity more accurately since they encompass a range of natural and agronomic selection pressures.

Wild oat (*Avena fatua* L.) is a competitive annual grass weed found throughout western Canada. In Alberta, wild oat is the second most abundant weed among cultivated field crops, present in 46 % of fields (Leeson et al. 2002). Wild oat is an economically important weed responsible for lost farm revenue, due to the use of costly herbicides and reductions in crop yield and quality. Management of wild oat in Alberta is complicated by the existence of biotypes resistant to Group 1 (acetyl- CoA-carboxylase (ACCase) inhibitor), Group 2 (acetolactate synthase (ALS) inhibitor) and Group 1 and 2 herbicides (Beckie et al. 2008b). Currently, delaying herbicide resistance in wild oat populations can be accomplished using reduced herbicide rates in conjunction with increasing crop competitiveness (Beckie and Kirkland 2003).

Integrating several agronomic practices which increase crop competitiveness and reduce wild oat density can reduce the contribution of seed to the seedbank. O'Donovan et al. (2006) found a decrease in the number of wild oat seeds returned to the seedbank when wheat seeding rate was increased in conjunction with full rates of herbicide. Similarly, Blackshaw et al. (2005a) found in wheat (*Triticum aestivum* L.)-canola (*Brassica napus* L.) rotations under zero tillage that a combination of increased seeding rates and spring application of mid-row banded nitrogen reduced the number of weed seeds in the seedbank up to 49%. Although wild oat is not a prolific seed producer, fecundity under no crop competition can average between 100 to 150 seeds plant^{-1} (Sharma and Vanden Born 1978). Seed shatter in wild oat typically occurs prior to crop maturity; whereby, 80% of wild oat seeds are shed prior to spring wheat harvested at 20% moisture (Shirtliffe et al. 2000). While seed shatter prior to crop maturity minimizes the dispersal of wild oat during harvest (Shirtliffe et al. 2000), the seeds are a significant contribution to the seed bank.

Wild oat has a persistent seed bank, whereby seeds typically remain viable for 4 to 6 years (Banting 1962; Banting 1966). In a seed cage burial study, Banting (1966) measured wild oat seed viability at 0-25cm depths within a heavy clay soil from Regina, Saskatchewan. A rapid reduction in wild oat seed viability occurred within the first two years, with only 8% of seeds remaining viable; however, remaining viable seeds persisted up to 6 years and 8 months. In addition, the greatest loss of seed viability occurred near the soil surface (0-5cm) than at depths greater than 5 cm. The persistence of wild oat seeds is largely attributed to primary and secondary dormancy. Primary dormancy in wild oat is typically overcome by a period of after-ripening under warm, dry conditions (Myers et al. 1997); however, after an extended period of after-ripening, seeds can enter and re-enter secondary dormancy, which can occur over many successive seasons (Hou et al. 1997). The cycles of secondary dormancy ensures an intermittent emergence of seedlings, allowing a proportion of seedlings to survive and produce seed within a year. Consequently, encouraging growers to integrate cropping practices that incorporate the use of reduced herbicide rates may be hindered without an increased understanding of how wild oat seed inputs and removals influence the persistence and long term dynamics of seed banks (Maxwell et al. 2007).

A better understanding of the cumulative effects of integrating agronomic practices on seed bank dynamics is essential to managing wild oat populations. Furthermore, determining the extent of future wild oat problems using wild oat seedling emergence, biomass and seed production information may ensure timely and effective weed management strategies are implemented. The objectives of this experiment are to: (1) identify the cumulative impact of the interactions between continuous and more diverse barley (*Hordeum vulgare* L.) rotations with low and high seeding rates and short and tall barley cultivars under quarter, half and full herbicide rates on wild oat seed bank dynamics (2) determine the relationship between wild oat seed banks and seedling emergence (3) determine if wild oat seed banks can be predicted from wild oat seedling emergence, biomass and seed production.

3.2. Materials and Methods

3.2.1. Site Description

Field experiments were conducted in 2006 and 2007 in conjunction with a seven year Agriculture and Agri-Food Canada (AAFC) integrated cropping systems project (Harker et al. 2009), established at Beaverlodge (55°13' N, 119°24' W), Fort Vermilion (58°24′ N, 116°0′ W) and Lacombe (52°27' N, 113°45' W), Alberta. Mean air temperature and precipitation data for Beaverlodge, Fort Vermilion and Lacombe were recorded between 2005 and 2007 (Appendix 1, Figure A1.1.). The clay loam soil (29% sand, 42% silt and 29% clay) at Beaverlodge, AB was a Dark Gray Luvisol (Typic Cryoboroll) with pH 5.9 and 6.6 % organic matter. The Dark Gray Luvisol soil (Typic Cryoboroll) at Fort Vermilion, AB was a sandy loam soil (50% sand, 43% silt and 7% clay) with pH 6.8 and 3.3% organic matter. The loam soil (51% sand, 30% silt and 19% clay) at Lacombe, AB was an Orthic Black Chernozem (Typic Haplustoll) with a pH of 6.6 and 7.8% organic matter.

3.2.2. Cropping System

The initial experiment designed by Harker et al. (2009) quantified the impact of crop rotation, barley cultivar, barley seeding rate, and post emergent wild oat herbicide rate and their interactions on barley yield, wild oat management and environmental and economic sustainability.

To test for interactions, treatments were imposed in a factorial arrangement and randomized in a complete block design with four replicates in each of three locations. Vivar (Short) and AC Lacombe (Tall) barley varieties were compared within a continuous barley rotation (Cont) and a more diverse rotation (Rot) of barley-canola-barley-pea (*Pisum sativum* L.). A full description of the experimental sites and plot maintenance from 2001 to 2005 is summarized in Harker et al. (2009); 2006 to 2007 site information and plot maintenance is documented in Tables 3.1, 3.2 and 3.3 .

Plots were direct seeded at all locations in May (Table 3.2.) with a ConservaPak[1] air seeder with 1 cm wide knife openers and 23 cm row spacing. Plot size was 3 by 15 m. A single application of N, P_2O_5, K_2O and S fertilizers were side banded at seeding according to soil test recommendations. Barley was seeded at either 200 seeds m^{-2} (1x) or 400 seeds m^{-2} (2x) at a 3 cm depth, canola (InVigor 5020) was seeded 150 seeds m^{-2} at a depth of 1 cm. Thousand kernel weights were used to adjust seeding rates to achieve target plant populations. To delineate management systems and to maintain consistency in discussion, the short cultivar, 1x barley seeding rate and continuous barley rotation will be referred to as the "low management" system (i.e. Short-1x-Cont) whereas the tall cultivar, 2x barley seeding rate and diversified barley rotation will be referred to as the "high management" system (i.e. Tall-2x-Rot).

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[1] Conserva Pak Air Seeder, Model CP 129A. Conserva Pak Seeding Systems / Division of Vale Farms Ltd., PO Box 1420, Indian Head, SK, Canada S0G 2K0.

In 2006 and 2007, experimental areas received a glyphosate[2] pre-seed application (450 to 900 g ae ha^{-1}) to remove weeds. At the three-leaf stage in canola and the three- to four-leaf stage in barley, post-emergent wild oat herbicides were applied at 25%, 50% and 100% of the recommended rates in combination with full recommended rates of broadleaf herbicides (Table 3.3.). Within the continuous barley and barley rotational plots, barley variety, seeding rate and herbicide rate were repeated in the same plots across all years. Similarly, in the barley rotational plots seeded to peas or canola, a 25, 50 and 100% wild oat herbicide rate was repeatedly applied to the same plot throughout the crop rotation.

3.2.3. Data Collection

3.2.3.1. Seed Bank Sampling

Wild oat seed banks at all three locations were sampled prior to seeding and after harvesting (Table 3.2.). An extended W pattern was used to take ten soil cores from each plot, keeping within two rows from each edge and one meter from the front and back of the plot. Prior to sampling soil, chaff on the soil surface was removed within a 10.8 cm diameter circular ring. A soil core was immediately collected to a 5 cm depth below the sampled area and bulked with collected chaff. The ten samples were bulked into one sample per plot. Soil

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[2] Roundup, Roundup Transorb, or Roundup WeatherMax. Monsanto Canada Inc. 67 Scurfield Blvd. Winnipeg, MB, Canada R3Y 1G4.

samples were air-dried (~25°C) immediately for five to seven days to prevent germination. Germinated seed found in samples were counted and removed. Germinated seeds included both newly germinated as well as those exposed to fatal germination in the field. Dry weights were taken prior to returning sample to a dry plastic bag for storage (data not shown). To retrieve seeds, soil samples were first placed through an 8mm sieve to remove large pieces of straw and rocks and then through a 1mm sieve to remove fine soil particles. In the remaining sample, wild oat seeds were separated from soil by hand and stored separately in paper coin envelopes in a 5°C dark cool room.

3.2.3.2. Emergence, Biomass and Seed Production

The 2006 and 2007 wild oat emergence, biomass and seed production data from Beaverlodge, Fort Vermilion and Lacombe, AB. were retained from AAFC. Data were collected as outlined in Harker et al. (2009). Wild oat emergence, biomass and seed production data were counted from two permanent 0.91 m^{-2} quadrats in each plot. Wild oat emergence was recorded prior to post-emergent herbicide applications. Aboveground wild oat biomass was recorded prior to crop maturity or prior to wild oat shattering. The wild oat biomass was dried at low temperatures (30°C) and seeds threshed and counted. Wild oat seeds were returned to the original quadrat in each plot.

3.2.3.2. Seed Mortality Assessment

Wild oat seeds retrieved from each soil sample were counted prior to germination testing. Each sample was equally divided into three subsamples, whereby each subsample was limited to no more than 100 seeds and was planted at three different time intervals. Germination testing on seeds retrieved in the spring and fall of 2006 and 2007 began in the spring of 2007 and 2008, respectively, and commenced for four months. Each subsample was placed into a 24 cm by 16 cm by 4 cm germination box containing a 23 cm by 15 cm Hoffman #601 blotting paper. Blotting papers were moistened with 14 ml of distilled water. Germination boxes were kept in a growth chamber for ten days with a 20:4h light:dark photoperiod and light:dark temperatures of 21:18°C. Germinated seeds with a healthy protruding radicle were counted and removed. Non-germinated seeds that were soft and/or discolored were considered non-viable. Firm and intact seeds that remained non-germinated were tested for viability. These seeds were bisected longitudinally and placed embryo side down into a 10 cm diameter plastic petri dish containing a No. 1 Whatman filter paper moistened with a 0.15% solution of 2,3,5-triphenyltetrazolium chloride (TTC). Petri dishes were incubated in the dark at room temperature for two hours. Categorization of viable or non-viable seeds was based on the integrity of the embryo and tissue surrounding the embryo and staining pattern (Grabe 1970).

Seed mortality is defined as the total number of non-viable seeds (i.e. seeds that did not geminate and non-viable seeds from tetrazolium test). Wild oat seed mortality percentage (SMP) was calculated:

$$\mathrm{SMP} = ((\sum_{NV})/ (\sum_{NT})) \cdot 100 \qquad [1]$$

where, NV is the total number of non-viable seeds from each subsample and NT is the total number of seeds used in each subsample. The proportion of seed mortality was a direct inverse of seed viability (ie. total number of viable and germinated seeds).

3.2.4. Statistical Analyses

Residuals were tested for normality and heterogeneity using PROC GLIMMIX (Littell et al. 2006). Data from the wild oat seed bank densities, emergence, seed production and biomass indicated a right skewed distribution and variance heterogeneity; therefore, to account for nonnormality, a logarithmic transformation ($\log_{10}(x+1)$) was performed. Wild oat seed mortality percentages (SMP) did not require a transformation as data was normally distributed.

Wild oat seed bank densities and SMP were analyzed using PROC MIXED of SAS (Littell et al. 2006) whereby location and replicate were treated as random effects. Crop rotation, seeding rate, barley variety and herbicide rate were considered fixed effects. The significance of main effects and their interactions were determined for each variable (not shown). Contrasts were used to compare agronomic treatments (crop rotation, barley cultivar and barley seeding rate) within herbicide rates, as well as to compare low and high management systems among herbicide rates. Using Bonferroni adjustments, contrasts of fixed effects were considered significant at $P < 0.004$.

A simple regression using PROC REG in SAS (Freund and Littell 2000) was used to identify the relationship between log-transformed wild oat emergence and log-transformed wild oat seed bank density across all locations. More specifically, the relationship between fall 2006 seed banks and 2007 wild oat emergence and the relationship between spring 2007 seed banks with 2007 wild oat emergence were examined . The relationship was described using a simple linear model:

$$y = a + bx \qquad [1]$$

where, y is the dependent variable (log-transformed wild oat emergence), a is the intercept, b is the regression coefficient or slope and x is the independent variable (log-transformed wild oat seed bank densities).

Multiple linear regressions (PROC REG) were used to identify the value of using wild oat emergence, seed production and/or biomass data in predicting spring and fall wild oat seed banks, including all locations and by location. A multiplicative regression model,

$$y= (e^{\beta 0})(x_1^{\beta 1})(x_2^{\beta 2})(x_3^{\beta 3})(e^{\varepsilon}) \qquad [2]$$

where, $e^{\beta 0}$ is the intercept, β1, β2, β3 are the coefficients (elasticities) of $x_{1,}$ $x_{2,}$ x_3 which correspond to the biomass, emergence and seed production variables, respectively, and e^{ε} is the error component was converted to a linear model. The logarithms of both the independent and dependent variables were taken (Freund and Littell 2000) to develop the following linear model:

$$\log(y)= \beta_0+\beta_1(\log(x_1))+ \beta_2(\log(x_2))+ \beta_3(\log(x_3))+(\varepsilon) \qquad [3]$$

The inclusion of three independent variables (emergence, seed production and biomass) resulted in multicollinearity, i.e. a high degree of variable correlation among the independent variables. To reduce multicollinearity and improve the predictive power of the model, a stepwise selection procedure in SAS

(Freund and Littell 2000) was used for each regression,whereby variables included into the model were significant at 0.05.

3.3. Results and Discussion

3.3.1. Wild Oat Seed Bank Density

Wild oat seed bank densities for 2006 and 2007 were a culmination of both viable and non-viable seeds. Crop rotation, seeding rate, barley variety and herbicide rate had an effect on wild oat seed bank density ($P<0.05$) in the spring and fall of 2006 and 2007, but interaction effects were not significant (data not shown).

3.3.1.1. Spring 2006

The seed bank sampled in the spring of 2006 reflects the cumulative impact of treatments imposed over five years as well as the additions and losses from the seed bank from the 2005 cropping season. Significantly fewer wild oat seed accumulated in the seed bank when high cultural management (Tall-2x-Rot) techniques were employed compared to low management (Short-1x-Cont) techniques (Figure 3.1.). Harker et al. (2009) also reported a similar trend reflected among wild oat emergence, biomass and seed production during the 2005 growing season.

Within the quarter herbicide treatments, crop rotation ($P<0.0001$) and a higher barley seeding rate ($P= 0.0025$) had a significant impact on the wild oat seed bank. In the continuous rotation, only the Tall-2X treatment was significantly effective compared to the Short-1X in minimizing the wild oat seed bank. In the rotation treatments (Rot), all treatments were effective in reducing the amount of wild oat seed when compared with the low management treatment. Wild oat seed bank density from the high management system within the quarter herbicide rate was not significantly different from using a half or full rate of herbicide under low management. Thus, a high management system was as effective as using higher rates of herbicides.

Within the half rate herbicide treatments, high management strategies reduced wild oat seed banks compared to low management strategies. Treatments that combined a 2X vs. 1X seeding rate ($P<0.0001$), a Tall vs. Short barley cultivar ($P=0.0012$) and a diverse crop rotation over a continuous barley rotation ($P<0.0001$) resulted in fewer wild oat seed in the seed bank. Under the continuous rotation, each treatment with the exception of the Tall-1X treatment resulted in less wild oat seed when compared to the Short-1X treatment. Similarly, the Short-1X-Rot was the only treatment among the Rot treatments that did not differ from the Short-1X-Cont treatment.

Within the full herbicide rate, all treatments except the Short-2X-Cont reduced the wild oat seed bank compared to the Short-1X-Cont treatment. Contrasts indicate that Tall vs. Short ($P=0.0022$) was the most effective wild oat management strategy.

3.3.1.2. Fall 2006

The fall 2006 seed bank reflects wild oat seed inputs and losses from the 2006 cropping season in addition to reserves from previous cropping seasons. More wild oat seed was retrieved from the fall seed bank than the spring, reflecting additional seed bank inputs during the 2006 cropping season. Large inputs of weed seeds to the soil seed bank typically occur from weed seed rain (Norris 2007). Many factors influence the amount of weed seed production including weed and crop species (Clay et al. 2005; Davis 2008; Holman et al. 2006; Lutman 2002), crop seeding rate (O'Donovan et al. 2007b), weed emergence periodicity (Blackshaw and Harker 1997) and soil fertility (O'Donovan et al. 2008; Van Delden et al. 2002). Despite additional seed inputs, the impact of treatments continued to be reflected from the spring to fall seed bank (Figure 3.1.). In addition, wild oat seed banks under high management systems across all three herbicide rates continued to have significantly fewer seeds than low management treatments.

In the quarter herbicide rate, contrasts indicate that a higher barley seeding rate (P=0.0006) resulted in fewer wild oat seed in the seed bank. Consequently, the Tall-2X-Rot (526 seeds m^{-2}) and Short-2X-Rot (805 seeds m^{-2}) were the only treatments that had significantly less wild oat seed compared to the low management system (Short-1X-Cont) (2867 seeds m^{-2}).

Combining crop rotation (P<0.0001) and a higher barley seeding rate (P=0.0014) continued to yield fewer wild oat seeds in the fall seed bank under the half herbicide rates. All treatments except the 1X-Short-Cont and 1X-Tall-Cont reduced the amount of seed in the wild oat seed bank.

Lastly, under the full herbicide rate, crop rotation was the most optimal cultural technique to have an effect on the wild oat seed bank (P=0.0004). The high management system at the half herbicide rate did result in fewer seeds than the low management at the full herbicide rate, but not significantly (P=0.0711). However, the quarter herbicide rate with high management system resulted in significantly more wild oat seed than the full rate of herbicide with a low management system (P<0.0001). In this instance, management changes could not fully replace the effectiveness of herbicides.

3.3.1.3. Spring 2007

The cumulative impact of six years of treatments and the biological processes influencing seed bank additions and losses are reflected in the spring 2007 seed bank. Similar to the spring and fall 2006 wild oat seed banks, high management systems (Tall-2X-Rot) effectively reduced the amount of seeds in the spring 2007 seed bank compared to low management systems (Short-1X-Cont) across all herbicide rates (Figure 3.2.).

Within the quarter herbicide rate treatments, contrasts indicated seeding rate had the most significant impact on wild oat seed bank density (P=0.0002). The Tall-2X treatment in both Cont and Rot treatments had significantly fewer wild oat seeds in the seed bank than the Short-1X-Cont. Using the high management system with only a quarter herbicide rate, wild oat seed bank density did not significantly differ from using a half rate of herbicide with a low management system (P=0.6510); however a significantly higher wild oat seed bank resulted from the high management system at the quarter herbicide rate compared to a full rate of herbicide with a low management system (P<0.0001).

Increased seeding rate (P<0.0001) and crop rotation (P<0.0001) both significantly reduced the wild oat seed bank density at the half herbicide rate. Only the Short-2X-Cont and Tall-1X-Cont were not significantly different from the low management system (Short-1X-Cont).

At the full herbicide rate, diverse crop rotation, higher seeding rates or competitive barley cultivars did not significantly reduce wild oat seed bank densities. In general, treatments within the Rot had significantly less wild oat seed compared to the Short-1X-Cont; whereas no differences were identified between the Short-1X-Cont and treatments within the Cont treatments.

In general, fewer seeds were retrieved from the spring 2007 seed bank compared to the fall 2006 seed bank. The amount of seed lost between spring and fall ranged from 0 to 65% whereby greater seed losses occurred under treatments that had larger wild oat seed banks. The decline in the wild oat seed bank between fall 2006 and spring 2007 may be a function of post seed dispersal predation (Cromar et al. 1999), microbial and fungal decay (Gallandt et al. 2004; Mickelson and Grey 2006) and/or degradation from extreme environmental conditions (Murphy et al. 2006). Nevertheless, the magnitude of seed loss between fall and spring wild oat seed banks requires additional attention. Identifying and augmenting losses in the wild oat seed bank may not only improve the impact of IWM strategies but reduce the persistence of wild oat in western Canada. Conversely, in some low density wild oat seed banks, more seeds were retrieved in the spring 2007 than fall 2006 seed banks; for example, in the Half-Tall-1X-Cont, 55 more seeds m^{-2} were found in the spring 2007 than fall 2006. Despite randomly sampling plots each spring and fall, variability in the number of seeds sampled may be attributed to various levels of seed aggregation influenced by differences in plant morphology, seed dispersal and agricultural practices (Chauvel et al. 1989).

3.3.1.4. Fall 2007

The fall 2007 seed bank is a culmination of seed additions and losses over seven years. Similar to 2006, higher accumulations of wild oat seeds were observed in the seed bank compared to spring 2007 seed bank assessments, reflecting seasonal seed rain. Nevertheless, high management systems continued to exhibit smaller wild oat seed banks than low management systems (Figure 3.2.).

At the quarter herbicide, higher barley seeding rates had a substantial impact on reducing wild oat seed bank densities (P=0.0008). The Tall-2X-Rot (1123 seeds m^{-2}) had significantly fewer wild oat seeds in the seed bank than the Short-1X-Cont (4323 seeds m^{-2}). Similar to the spring 2007 seed bank, using good agronomic practices with only a quarter herbicide rate did not significantly differ from using a half rate of herbicide with a low management system (P=0.5040);

however, using a full rate of herbicide within a low management system still resulted in fewer wild oat seeds in the seed bank than using a quarter herbicide rate under high management (P<0.0001).

At the half herbicide rate, higher seeding rate (P<0.0001) and crop rotation (P<0.0001) were key management strategies in minimizing the wild oat seed bank. Only the Tall-1X-Cont did not differ significantly from the low management system (Short-1X-Cont). In addition, fewer wild oat seed were retrieved under the high management system at half herbicide rate (Tall-2X-Rot) compared to the low management system (Short-1X-Cont) at the full herbicide rate, but the difference was not significant (P=0.0703).

Under full herbicide rates, higher seeding rates resulted in the lowest wild oat seed bank densities (P=0.0042). Under the continuous and diverse rotations, Tall-2X and Short-2X treatments had smaller wild oat seed banks than the Short-1X-Cont treatment.

Combining a competitive barley cultivar with increased barley seeding rate and diverse crop rotation were consistent with Harker et al. (2009) study, which reported reductions in wild oat seed production, biomass and emergence under high management systems. Furthermore, the benefits of using competitive cultivars, higher crop seeding rates and crop rotation to effectively manage weeds have been previously reported in western Canada and are consistent with the findings in this study. Growing competitive barley, wheat, canola or field pea cultivars has been an important agronomic strategy to enhance crop competitiveness (Beckie et al. 2008a; Harker et al. 2008; Hucl 1998; O'Donovan et al. 2005; Watson et al. 2006).

Among barley varieties, taller hulled barley varieties are more competitive with wild oat or tame oat (*Avena sativa* L.) than semi-dwarf and hull-less varieties (O'Donovan et al. 2000; Watson et al. 2006) and subsequently experience less yield loss (O'Donovan et al. 2000). Increased barley (O'Donovan et al. 1999; O'Donovan et al. 2000; O'Donovan et al. 2001), wheat (Blackshaw et al. 2000; O'Donovan et al. 2006; Xue and Stougaard 2002), field pea (Johnston et al. 2002) and canola (Hanson et al. 2008; Harker et al. 2003) seeding rates have also been used to successfully increase crop yield and decrease weed biomass. Increasing barley seeding rates from 200 to 250 plants m^{-2} can effectively reduce wild oat biomass and seed production and increase barley grain yield (O'Donovan et al. 1999; O'Donovan et al. 2000; O'Donovan et al. 2001). Crop rotation has been instrumental in managing weed populations by providing interference with the life cycle and growth habit of weeds (Anderson 2005). For example, wild oat densities were up to 22 times greater in continuous cereal fields than in a cereal crop preceded by an alfalfa (*Medicago sativa* L.) or alfalfa/hay crop (Ominski et al. 1999).

The impact of integrating agronomic practices with herbicide use on the long term effects of weed seed banks has not been widely studied in western Canada; however, results from this study are consistent with short-term seed bank studies carried out under cropping systems combining agronomic practices.

Blackshaw et al. (2005a) reported reductions in weed seed banks when spring wheat and canola seeding rates were increased from 100% to 150% of recommended rates and combined with spring fertilizer applications rather than fall fertilizer applications. Similarly, under reduced herbicide rates, O'Donovan et al. (2004) found lower densities of wild oat seeds in the seed bank when canola and barley seeding rates were increased; however, the impact of higher seeding rates became less evident as herbicide rates were increased to three quarter and full rates. Overall, maintaining low seed bank densities and subsequent seed additions through combined optimal agronomic practices and herbicide use are necessary to minimize future weed problems.

3.3.2. Wild Oat Seed Mortality

Seed mortality was examined to identify whether treatments had a direct or indirect impact on the number of non-viable seeds found within the seed bank. The seed mortality percent (SMP) reflects the number of seeds that did not germinate or were not viable from the tetrazolium testing. No main effects or interactions were found to significantly affect seed mortality (data not shown). In the spring and fall of 2006 and 2007, no significant differences among crop rotation, barely cultivar and barley seeding rate within quarter, half and full herbicide rates were identified (Figure 3.3. and Figure 3.4.).

Varying levels of seed viability and mortality are reflected in the seed bank as a result of a culmination of seed cohorts from previous cropping seasons. Seed mortality remained remarkably stable, even when crop rotation, barley variety and barley seeding rate were varied within each herbicide rate (Figure 3.3. and Figure 3.4.). The average rate of mortality across all treatments in spring and fall 2006 was 83 and 84%, respectively, and 56 and 76%, respectively, in the spring and fall 2007. Forcella (1992) reported >80% of the seed bank to consist of dead seeds, whereby a larger proportion of dead weeds seeds were found in the spring than in the fall. Implementing this trial under conservation tillage may have had a larger influence on seed mortality than the specific treatments. Long term agricultural management practices such as conservation tillage can influence soil microbial communities and have a significant impact on weed seed decay (Davis et al. 2006). In addition, seeds on the soil surface are exposed to extreme fluctuations in environmental conditions, physiological decay, exhaustion and predation (Buhler et al. 1997; Miller and Nalewaja 1990; Sagar and Mortimer 1976). For example, increased exposure to extreme environmental conditions, such as extreme temperatures or moisture enhanced seed reductions from the soil seed bank in zero tillage systems (Murphy et al. 2006). Exposing seeds to extreme wet conditions can weaken hard seed coats and create an opportunity for microbial infection to augment seed decay (Mickelson and Grey 2006; Schutte et al. 2008).

During the spring of 2007, percent seed mortality was lower at all three locations than in other seasons or years. Seeds that tested negative with the tetrazolium test may have been underestimated during the spring of 2007. In addition, several biological processes can influence seed mortality, including seed predation, extreme environmental conditions, seed aging, microbial decay and fatal germination; therefore, variability in samples collected and used for germination testing may have reflected a different set of biological interactions.

3.3.3. Relationship between Wild Oat Seed Bank Density and Seedling Emergence

Using seed bank data to predict weed emergence can be an important tool for growers in predicting future weed problems and developing appropriate weed management strategies (Buhler et al. 1997). However, research studies that have investigated the relationship between weed seed banks and weed seedling emergence have been variable, ranging from highly to poorly correlated (Webster et al. 2003). In this study, a linear relationship between the fall 2006 logarithmic wild oat seed bank density and 2007 logarithmic wild oat emergence (R^2=0.76; Figure 3.5.) as well as between the spring 2007 logarithmic wild oat seed bank density and 2007 logarithmic wild oat emergence (R^2=0.78; Figure 3.6.) were established. As a result, estimates from the spring or fall seedbank show astrong relationship with wild oat emergence.

Furthermore, larger wild oat seed banks had proportionally fewer emerged seedlings than smaller wild oat seed banks. Similarly, Boyd and Van Acker (2004) reported fewer wild oat seeds proportionally emerging with increasing seeding density. As the density of seeds increase, more seeds are likely to exist within microsites unsuitable for germination or more suitable to promote re-entry of secondary dormancy (Boyd and Van Acker 2004). Furthermore, within larger seed banks, cohorts of seed may exist from multiple generations, whereby a range of dormancy states are expressed within each generation resulting in more variable emergence (Batlla and Benech-Arnold 2007).

3.3.4. Relationship between Wild Oat Seed Bank Density, Biomass, Emergence and Seed Production

Across all three locations, wild oat biomass and emergence were the most significant predictors of the fall and spring wild oat seed bank (Table 3.4.). Similarly, after separation of spring and fall seed banks by location, 9 out of 12 occurrences indicated emergence as the most consistent predictor of the wild oat seed bank density (Table 3.5.). However, wild oat biomass and seed production were also important variables in 7 and 6 locations, respectively. Emergence was not a significant predictor of the spring 2006 Beaverlodge, fall 2007 Fort Vermilion and fall 2007 Lacombe seed banks, but biomass or seed production were. These results were surprising as it was our hypothesis that wild oat seed production would also be a consistent predictor of seed bank density. One reason for this discrepancy may be some shattering loss of wild oat seed prior to seed production assessments, which may have underestimated the predictive value of this variable. Furthermore, the wild oat seed bank reflects multiple seed cohorts, whereby the total number of seeds in the seed bank reflects multiple years of seed additions and losses. Consequently, the complexity and variability among weed seed banks across geographic areas highlights the difficulty in developing comprehensive weed management programs for wild oat.

3.3.5. Management Implications

Integrating optimal agronomic practices such as competitive cultivars, higher barley seeding rates and diverse crop rotations effectively minimized wild oat seed bank densities. Occasionally, combining optimal agronomic practices under half herbicide rates did result in equivalent or smaller wild oat seed banks than full herbicide rates under low management. However, a higher wild oat seed bank density typically occurred under high management systems with quarter herbicide rate compared to low management at full herbicide rate. Consequently, herbicides will continue to be an important component in IWM systems for managing wild oat populations. However, growers that repeatedly implement a combination of optimal agronomic practices may have the opportunity to reduce herbicide rates or the number of herbicide applications over time.

Optimizing management practices under reduced herbicide rates can improve crop health and productivity, herbicide resistance management and farm profitability (Harker et al. 2009). Harker et al. (2009) demonstrated that adopting high management strategies was also beneficial in preserving barley yields. After 5 years of IWM, barley yields within high management systems at reduced herbicide rates were higher than yields within the low management system using higher herbicide rate. In addition, reducing herbicide rates can decrease the selection pressure for herbicide resistance of target-site herbicides (Beckie and Kirkland 2003). Combining high management practices with reductions in herbicide rates can be instrumental in reducing the number of resistant seeds in the seed bank without increasing the overall seed bank and reducing the recruitment of herbicide resistant seedlings (Beckie and Kirkland 2003).

Several biological processes are involved in regulating and regenerating seed banks (Buhler et al. 1997). Adopting integrated weed management practices to prevent or minimize seed return is essential to managing wild oat seed banks. Implementing high management practices can provide an opportunity to minimize seed return and maintain a small wild oat seed bank. Similarly, additional knowledge is needed to understand the mechanisms by which seeds are lost from the wild oat seed bank. Direct seeding can play an important role in minimizing the amount of seed in the seed bank. Murphy et al. (2006) found an increase incidence of herbivory and pathogenic infection on weeds in zero tillage cropping systems. The ability to enhance weed seed losses from cropping systems can have important long term weed management implications.

The relationship between emergence and seed bank indicate that spring and fall seed banks can generally be used as a good indicator of wild oat emergence. Developing better weed emergence models for growers and agricultural professionals to complement current IWM strategies will require additional information wild oat seed production, emergence, biomass and seed banks from across geographic regions in western Canada.

Table 3.1. Summay of treatments at Beaverlodge, Fort Vermilion and Lacombe, Alberta between 2001-2007.

Rotation[a]	**Year/ Crop**[b,c,d]							**Barley Seeding Rate**[e]	**Herbicide Rates**
	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**		
Cont	SB	SB	SB	SB	SB	SB	SB	Normal	Quarter
Cont	SB	SB	SB	SB	SB	SB	SB	Normal	Half
Cont	SB	SB	SB	SB	SB	SB	SB	Normal	Full
Cont	SB	SB	SB	SB	SB	SB	SB	Double	Quarter
Cont	SB	SB	SB	SB	SB	SB	SB	Double	Half
Cont	SB	SB	SB	SB	SB	SB	SB	Double	Full
Cont	TB	TB	TB	TB	TB	TB	TB	Normal	Quarter
Cont	TB	TB	TB	TB	TB	TB	TB	Normal	Half
Cont	TB	TB	TB	TB	TB	TB	TB	Normal	Full
Cont	TB	TB	TB	TB	TB	TB	TB	Double	Quarter
Cont	TB	TB	TB	TB	TB	TB	TB	Double	Half
Cont	TB	TB	TB	TB	TB	TB	TB	Double	Full
Rot	SB	Canola	SB	Peas	SB	Canola	SB	Normal	Quarter
Rot	SB	Canola	SB	Peas	SB	Canola	SB	Normal	Half
Rot	SB	Canola	SB	Peas	SB	Canola	SB	Normal	Full
Rot	SB	Canola	SB	Peas	SB	Canola	SB	Double	Quarter
Rot	SB	Canola	SB	Peas	SB	Canola	SB	Double	Half
Rot	SB	Canola	SB	Peas	SB	Canola	SB	Double	Full
Rot	TB	Canola	TB	Peas	TB	Canola	TB	Normal	Quarter
Rot	TB	Canola	TB	Peas	TB	Canola	TB	Normal	Half
Rot	TB	Canola	TB	Peas	TB	Canola	TB	Normal	Full
Rot	TB	Canola	TB	Peas	TB	Canola	TB	Double	Quarter
Rot	TB	Canola	TB	Peas	TB	Canola	TB	Double	Half
Rot	TB	Canola	TB	Peas	TB	Canola	TB	Double	Full

[a] **Rotation:** Cont- Continuous Rotation; Rot-Diverse Rotation

[b] **Crop:** Barley Variety: SB- Short Barley; TB- Tall Barley

[c] **Canola Seeding Rate:** Normal: 150 seeds m^{-2}

[d] **Pea Seeding Rate:** Normal: 150 seeds m^{-2}

[e] **Barley Seeding Rate:** Normal: 200 seeds m^{-2}; Double: 400 seeds m^{-2}

Table 3.2. Field operations and dates from 2006-2007 at Beaverlodge, Fort Vermilion and Lacombe, Alberta.

Field Operation	Year	Beaverlodge	Fort Vermillion	Lacombe
	2006			
Spring seed bank collection		May 5,6	May-09	May 2-3
Seeding (barley, canola)		May-16	May-12	May-04
Barley harvest		Aug. 29, 30	Sept. 7, 8	Aug.16, 18
Canola harvest		Aug. 29, 30	Sept. 18, 19	n/a[b]
Fall seed bank collection		Sept. 28	Sept. 29	Oct. 4
	2007			
Spring seed bank collection		May-14	May-15	May-01
Seeding (barley)		May-17	May-18	May-11
Barley harvest		Sept. 25, Oct. 15 [a]	Sept. 13	Sept. 17
Fall seed bank collection		Oct. 16	Sept. 24	Sept. 20

[a] AC Lacombe barley harvested before Vivar harvested Oct. 15.

[b] No harvest as canola swaths were displaced by wind

Table 3.3. Herbicide applications and dates from 2006-2007 at Beaverlodge, Fort Vermilion and Lacombe, Alberta.[a]

Crop	**Year**	**Herbicide**	**Herbicide Rate (g ai ha^{-1})**	**Beaverlodge**	**Fort Vermilion**	**Lacombe**
Barley	2006	Fenoxaprop-p-ethyl[b]	23, 46 or 93	June 13	June 13	May 31
		Quinclorac/Thifensulfuron/ Tribenuron[c]	50/15/15			
Canola	2006	Glufosinate[d]	125, 250 or 500	June 13	June 12	June 1
		Clethodim[e]	17, 34 or 67			
Barley	2007	Imazamethabenz[f]	125, 250 or 500	June 14/15	June 11	June 5
		Florasulam/MCPA ester[g]	5/240			

[a] When specified on product labels, herbicides were applied with recommended adjuvants.

[b] Puma Super 120: Bayer Crop Science Inc. #100, 3131 – 114 Ave. S.E., Calgary, AB, Canada T2Z 3X2.

[c] Triton C: DuPont Canada Inc. 4444 72 Ave. S.E. Calgary, AB T2C 2C1.

[d] Liberty: Bayer Crop Science Inc. #100, 3131 – 114 Ave. S.E., Calgary, AB, Canada T2Z 3X2.

[e] Select: Arysta LifeScience Canada Inc. 998, 105 – 150 Crowfoot Cres. N.W., Calgary, AB, Canada T3G 3T2.

[f] Assert 300: Nufarm Agriculture Inc. 5507 – 1st Street S.E. Calgary, AB T2H 1H9.

[g] Frontline: Dow AgroSciences Canada. #2100, 450 – 1st St. S.W. Calgary, AB T2P 5H1.

Table 3.4. The relationship between 2005, 2006 and 2007 log-transformed wild oat biomass and emergence with 2006 and 2007 spring and fall log-transformed wild oat seed bank densities across Beaverlodge, Fort Vermilion and Lacombe, Alberta.

Biomass, Emergence and Seed Production	**Seed bank**	**Estimate[a,b]**			**R^2**
		Intercept	**Biomass**	**Emergence**	
2005	Spring 2006	0.81 (<0.0001)	0.76 (<0.0001)	0.27 (<0.0001)	0.78
2006	Fall 2006	2.46 (<0.0001)	0.27 (<0.0001)	0.75 (<0.0001)	0.79
2006	Spring 2007	2.11 (<0.0001)	0.35 (<0.0001)	0.61 (<0.0001)	0.76
2007	Fall 2007	1.72 (<0.0001)	0.55 (<0.0001)	0.44 (<0.0001)	0.83

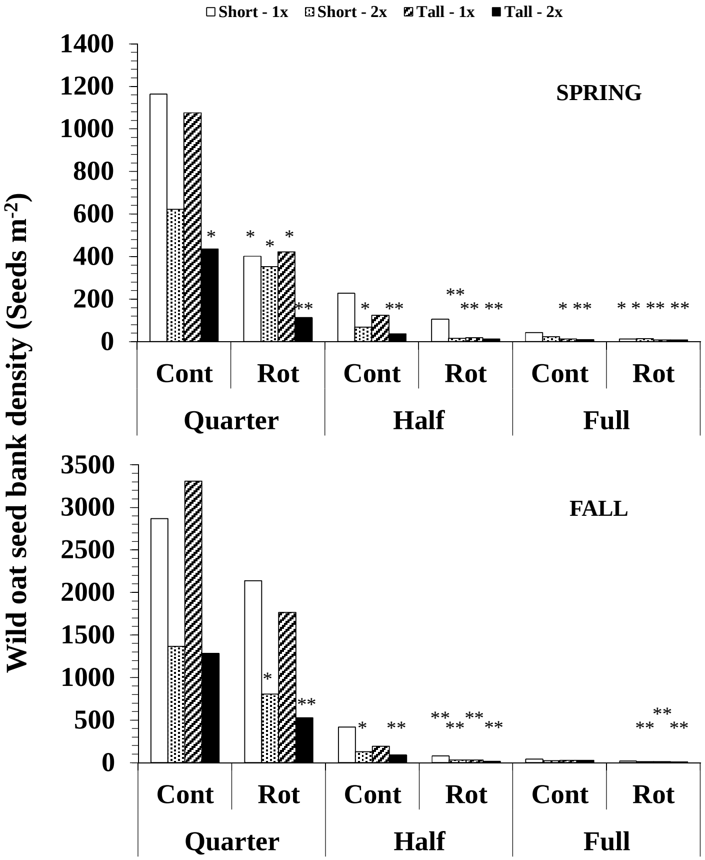
[a] Using stepwise multiple regressions, biomass and emergence were the remaining variables in each model significant at 0.05.

[b] p-values are listed beside each estimate value.

Table 3.5. The relationship between 2005, 2006 and 2007 log-transformed wild oat biomass, emergence and seed production with 2006 and 2007 spring and fall log-transformed wild oat seed bank densities at Beaverlodge, Fort Vermilion and Lacombe, Alberta.

Biomass, Emergence and Seed Production	Seed bank	Location	Estimate[a]				R^2
			Intercept	Biomass	Emergence	Seed Production	
2005	Spring 2006	Beaverlodge	0.63 (0.0204)	0.90 (<0.0001)			0.82
		Fort Vermilion	-0.39 (0.1316)		0.97 (<0.0001)	0.29 (0.0011)	0.61
		Lacombe	1.90 (<0.0001)		0.63 (<0.0001)	0.35 (<0.0001)	0.69
2006	Fall 2006	Beaverlodge	2.59 (<0.0001)	0.28 (<0.0001)	0.77 (<0.0001)		0.83
		Fort Vermilion	0.10 (0.8286)		0.64 (0.0070)	0.78 (<0.0001)	0.68
		Lacombe	2.32 (<0.0001)	0.52 (<0.0001)	0.30 (0.0177)		0.80
2006	Spring 2007	Beaverlodge	1.90 (<0.0001)	0.35 (<0.0001)	0.67 (<0.0001)		0.76
		Fort Vermilion	-0.26 (0.5541)		0.74 (<0.0001)	0.71 (<0.0001)	0.68
		Lacombe	2.36 (<0.0001)	0.40 (<0.0001)	0.44 (0.0009)		0.76
2007	Fall 2007	Beaverlodge	2.46 (<0.0001)	0.20 (0.0030)	0.55 (<0.0001)	0.13 (0.0333)	0.85
		Fort Vermilion	1.73 (<0.0001)	0.85 (<0.0001)			0.72
		Lacombe	4.10 (<0.0001)			0.50 (>0.0001)	0.78

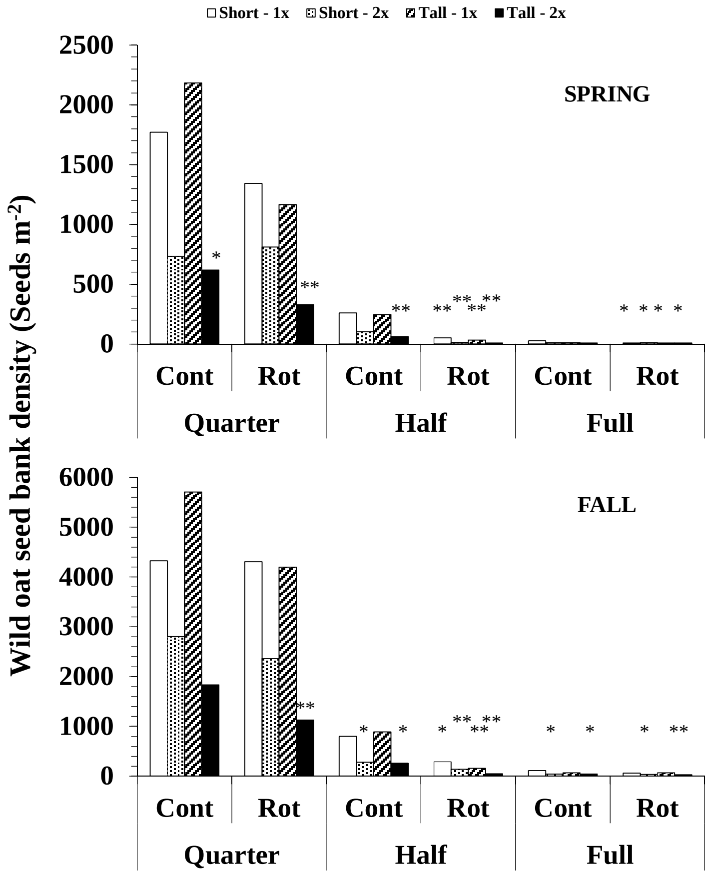
[a] Using stepwise multiples regressions, independent variables for each location were left in the model significant at 0.05.
[b] p-values are listed beside each estimate value.
[c] 2006 biomass data for Fort Vermilion is not included in the model.



Contrast	*P* value
¼ - Short vs Tall	0.1205
¼ - 1x vs 2x Seed	0.0025
¼ - Cont. vs Rot.	<0.0001
½ - Short vs Tall	0.0012
½ - 1x vs 2x Seed	<0.0001
½ - Cont. vs Rot.	<0.0001
Full - Short vs Tall	0.0022
Full - 1x vs 2x Seed	0.5292
Full - Cont. vs Rot.	0.0114
¼-Rot-Tall-2x vs ½-Cont-Short-1x	0.1535
¼-Rot-Tall-2x vs Full-Cont-Short-1x	0.0510
½-Rot-Tall-2x vs Full-Cont-Short-1x	0.0132

Contrast	*P* value
¼ - Short vs Tall	0.6291
¼ - 1x vs 2x Seed	0.0006
¼ - Cont. vs Rot.	0.0361
½ - Short vs Tall	0.0108
½ - 1x vs 2x Seed	0.0014
½ - Cont. vs Rot.	<0.0001
Full - Short vs Tall	0.3490
Full - 1x vs 2x Seed	0.1826
Full - Cont. vs Rot.	0.0004
¼-Rot-Tall-2x vs ½-Cont-Short-1x	0.6680
¼-Rot-Tall-2x vs Full-Cont-Short-1x	<0.0001
½-Rot-Tall-2x vs Full-Cont-Short-1x	0.0711

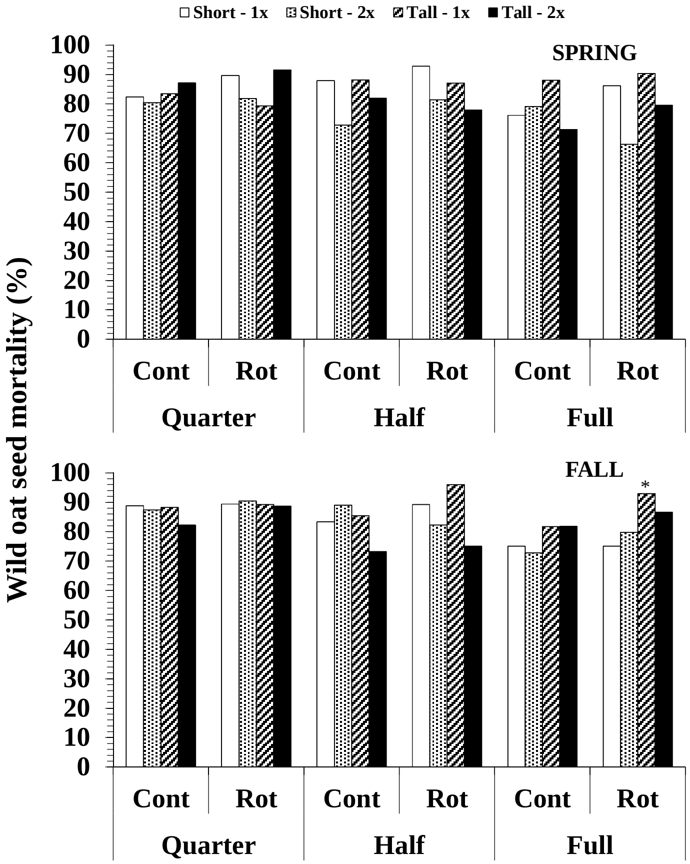
Figure 3.1. Mean wild oat seed bank density for the spring and fall of 2006 from Beaverlodge, Fort Vermilion and Lacombe, Alberta. Data are back-transformed means of log-transformed data. Pre-planned contrasts are listed beside each graph and are considered significant at $P < 0.004$. The statistical significance of the difference between a given log-mean and the Short-1x-Cont treatment within each quarter, half and full herbicide rate are denoted ‘*’ $P < 0.05$, ‘**’ $P < 0.01$.



Contrast	***P* value**
¼ - Short vs Tall	0.3312
¼ - 1x vs 2x Seed	0.0002
¼ - Cont. vs Rot.	0.1649
½ - Short vs Tall	0.1803
½ - 1x vs 2x Seed	<0.0001
½ - Cont. vs Rot.	<0.0001
Full - Short vs Tall	0.2115
Full - 1x vs 2x Seed	0.4191
Full - Cont. vs Rot.	0.1015
¼-Rot-Tall-2x vs ½-Cont-Short-1x	0.6510
¼-Rot-Tall-2x vs Full-Cont-Short-1x	<0.0001
½-Rot-Tall-2x vs Full-Cont-Short-1x	0.0429

Contrast	***P* value**
¼ - Short vs Tall	0.3758
¼ - 1x vs 2x Seed	0.0008
¼ - Cont. vs Rot.	0.3462
½ - Short vs Tall	0.1059
½ - 1x vs 2x Seed	<0.0001
½ - Cont. vs Rot.	<0.0001
Full - Short vs Tall	0.4771
Full - 1x vs 2x Seed	0.0042
Full - Cont. vs Rot.	0.2550
¼-Rot-Tall-2x vs ½-Cont-Short-1x	0.5040
¼-Rot-Tall-2x vs Full-Cont-Short-1x	<0.0001
½-Rot-Tall-2x vs Full-Cont-Short-1x	0.0703

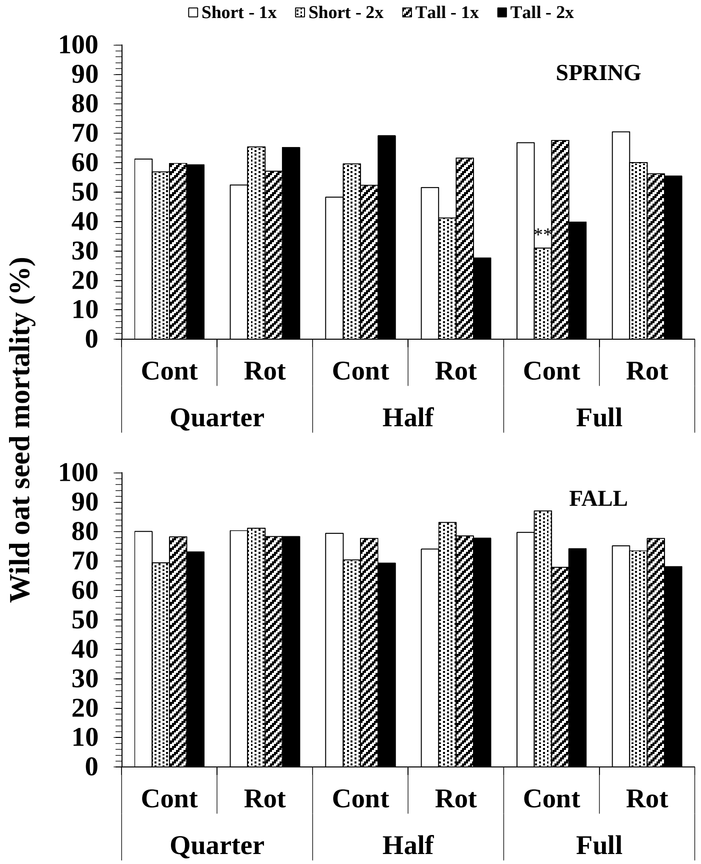
Figure 3.2. Mean wild oat seed bank density for the spring and fall of 2007 from Beaverlodge, Fort Vermilion and Lacombe, Alberta. Data are back-transformed means of log-transformed data. Pre-planned contrasts are listed beside each graph and are considered significant at $P < 0.004$. The statistical significance of the difference between a given log-mean and the Short-1x-Cont treatment within each quarter, half and full herbicide rate are denoted '*' $P < 0.05$, '**' $P < 0.01$.



Contrast	*P* value
¼ - Short vs Tall	0.6665
¼ - 1x vs 2x Seed	0.7040
¼ - Cont. vs Rot.	0.6365
½ - Short vs Tall	0.9824
½ - 1x vs 2x Seed	0.0334
½ - Cont. vs Rot.	0.6540
Full - Short vs Tall	0.2786
Full - 1x vs 2x Seed	0.0168
Full - Cont. vs Rot.	0.6076
¼-Rot-Tall-2x vs ½-Cont-Short-1x	0.6675
¼-Rot-Tall-2x vs Full-Cont-Short-1x	0.0741
½-Rot-Tall-2x vs Full-Cont-Short-1x	0.7492

Contrast	*P* value
¼ - Short vs Tall	0.5670
¼ - 1x vs 2x Seed	0.6235
¼ - Cont. vs Rot.	0.4370
½ - Short vs Tall	0.3770
½ - 1x vs 2x Seed	0.0289
½ - Cont. vs Rot.	0.4821
Full - Short vs Tall	0.0235
Full - 1x vs 2x Seed	0.7710
Full - Cont. vs Rot.	0.1665
¼-Rot-Tall-2x vs ½-Cont-Short-1x	0.4957
¼-Rot-Tall-2x vs Full-Cont-Short-1x	0.0882
½-Rot-Tall-2x vs Full-Cont-Short-1x	1.0000

Figure 3.3. Percent wild oat seed bank seed mortality for the spring and fall of 2006 from Beaverlodge, Fort Vermilion and Lacombe, Alberta. Data are reported as LSmeans. Pre-planned contrasts are listed beside each graph and are considered significant at P <0.004. The statistical significance of the difference between a given mean and the Short-1x-Cont treatment within each quarter, half and full herbicide rate are denoted '*' P < 0.05, '**' P < 0.01.



Contrast	*P* value
¼ - Short vs Tall	0.8234
¼ - 1x vs 2x Seed	0.4362
¼ - Cont. vs Rot.	0.9393
½ - Short vs Tall	0.8204
½ - 1x vs 2x Seed	0.4596
½ - Cont. vs Rot.	0.0446
Full - Short vs Tall	0.7398
Full - 1x vs 2x Seed	0.0166
Full - Cont. vs Rot.	0.2740
¼-Rot-Tall-2x vs ½-Cont-Short-1x	0.2182
¼-Rot-Tall-2x vs Full-Cont-Short-1x	0.8811
½-Rot-Tall-2x vs Full-Cont-Short-1x	0.0042

Contrast	*P* value
¼ - Short vs Tall	0.8244
¼ - 1x vs 2x Seed	0.3161
¼ - Cont. vs Rot.	0.2473
½ - Short vs Tall	0.8111
½ - 1x vs 2x Seed	0.6479
½ - Cont. vs Rot.	0.2980
Full - Short vs Tall	0.1121
Full - 1x vs 2x Seed	0.8764
Full - Cont. vs Rot.	0.3510
¼-Rot-Tall-2x vs ½-Cont-Short-1x	0.8889
¼-Rot-Tall-2x vs Full-Cont-Short-1x	0.8069
½-Rot-Tall-2x vs Full-Cont-Short-1x	0.8403

Figure 3.4. Percent wild oat seed bank seed mortality for the spring and fall of 2007 from Beaverlodge, Fort Vermilion and Lacombe, Alberta. Data are reported as LSmeans. Pre-planned contrasts are listed beside each graph and are considered significant at P <0.004. The statistical significance of the difference between a given mean and the Short-1x-Cont treatment within each quarter, half and full herbicide rate are denoted '*' P < 0.05, '**' P < 0.01.

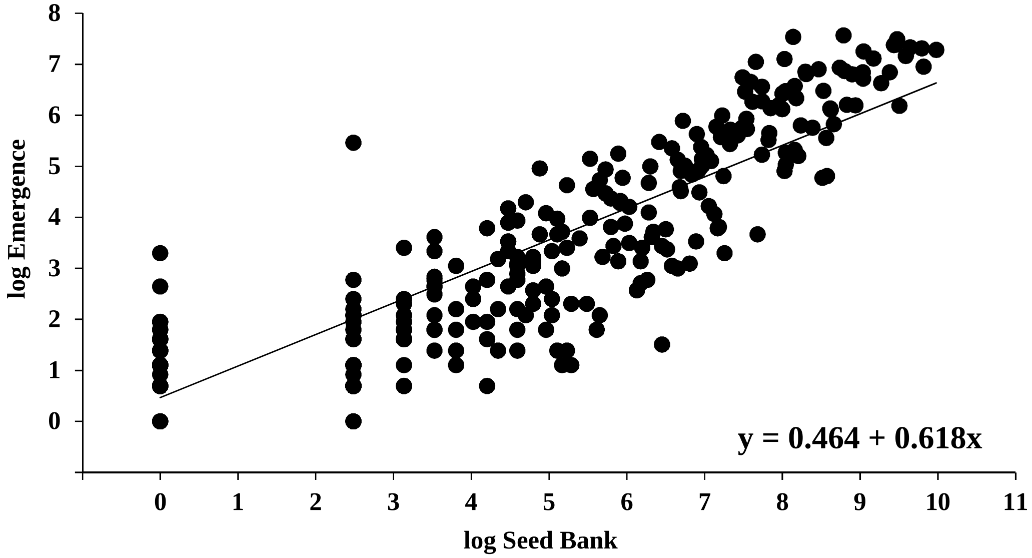


Figure 3.5. Linear relationship between 2006 fall wild oat seed bank and 2007 wild oat emergence from Beaverlodge, Fort Vermilion and Lacombe, Alberta. Symbol (●) represent log-transformed values and the line represents a fitted linear regression.

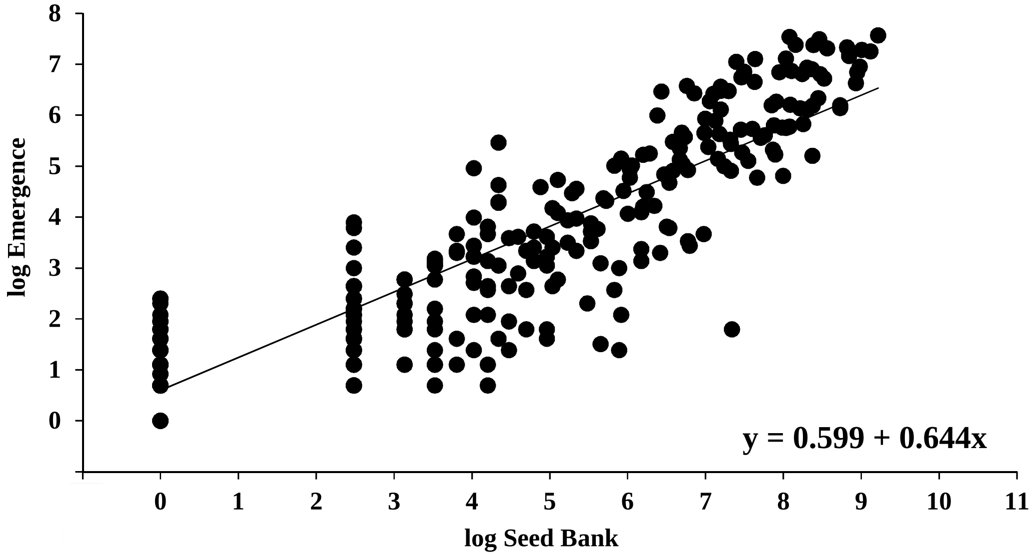


Figure 3.6. Linear relationship between 2007 spring wild oat seed bank and 2007 wild oat emergence from Beaverlodge, Fort Vermilion and Lacombe, Alberta. Symbol (●) represent log-transformed values and the line represents a fitted linear regression.

3.4. Literature Cited

Anderson, R. L. 2005. A multi-tactic approach to manage weed population dynamics in crop rotations. Agron. J. 97:1579-1583.

Banting, J. D. 1962. The dormancy behavior of *Avena fatua* L. in cultivated soil. Can. J. Plant Sci 42:22-39.

Banting, J. D. 1966. Studies on the persistence of *Avena fatua*. Can. J. Plant Sci 46:129-140.

Baskin C. C. and J. M. Baskin. 1998. Seeds: Ecology, biogeography, and evolution of dormancy and germination. San Diego, CA, USA: Academic Press. 666p.

Batlla, D. and R. L. Benech-Arnold. 2007. Predicting changes in dormancy level in weed seed soil banks: Implications for weed management. Crop Protect. 26:189-197.

Batlla D., B. C. Kruk, and R. L. Benech-Arnold. 2004. Modeling changes in dormancy in weed soil banks: Implications for the prediction of weed emergence. Pages 245-264 *In* R. L. Benech-Arnold and R. A. Sánchez, eds. Handbook of Seed Physiology. Applications to Agriculture. New York: Haworth Press, Inc.

Beckie, H. J., E. N. Johnson, R. E. Blackshaw, and Y. Gan. 2008a. Weed suppression by canola and mustard cultivars. Weed Technol. 22:182-185.

Beckie, H. J. and K. J. Kirkland. 2003. Implication of reduced herbicide rates on resistance enrichment in wild oat (*Avena fatua*). Weed Technol. 17:138-148.

Beckie, H. J., J. Y. Leeson, A. G. Thomas, C. A. Brenzil, L. M. Hall, and G. Holzgang. 2008b. Weed resistance monitoring in the Canadian Prairies. Weed Technol. 22:530-543.

Beckie, H. J., J. Y. Leeson, A. G. Thomas, L. M. Hall, and C. A. Brenzil. 2008c. Risk assessment of weed resistance in the Canadian Prairies. Weed Technol. 22:741-746.

Bekker, R. M., J. P. Bakker, U. Grandin, R. Kalamees, P. Milberg, P. Poschlod, K. Thompson, and J. H. Willems. 1998. Seed size, shape and vertical distribution in the soil: Indicators of seed longevity. Funct. Ecol. 12:834-842.

Belles, D. S., D. C. Thill, and B. Shafi. 2000. PP-604 rate and *Avena fatua* density effects on seed production and viability in *Hordeum vulgare*. Weed Sci. 48:378-384.

Bello, I. A., H. Hatterman-Valenti, and M. D. K. Owen. 1998. Effects of stratification, temperature, and oxygen on woolly cupgrass (*Eriochloa villosa*) seed dormancy. Weed Sci. 46:526-529.

Benech-Arnold, R. L., R. A. Sanchez, F. Forcella, B. C. Kruk, and C. M. Ghersa. 2000. Environmental control of dormancy in weed seed banks in soil. Field Crops Res. 67:105-122.

Benvenuti, S. 2007. Natural weed seed burial: Effect of soil texture, rain and seed characteristics. Seed Science Research 17:211-219.

Benvenuti, S., M. Macchia, and S. Miele. 2001. Quantitative analysis of emergence of seedlings from buried weed seeds with increasing soil depth. Weed Sci. 49:528-535.

Blackshaw, R. E., H. J. Beckie, L. J. Molnar, T. Entz, and J. R. Moyer. 2005a. Combining agronomic practices and herbicides improves weed management in wheat-canola rotations within zero-tillage production systems. Weed Sci. 53:528-535.

Blackshaw, R. E. and K. N. Harker. 1997. Scentless chamomile (*Matricaria perforata*) growth, development, and seed production. Weed Sci. 45:701-705.

Blackshaw, R. E., K. N. Harker, J. T. O'Donovan, H. J. Beckie, and E. G. Smith. 2008. Ongoing development of integrated weed management systems on the Canadian Prairies. Weed Sci. 56:146-150.

Blackshaw, R. E., J. R. Moyer, K. N. Harker, and G. W. Clayton. 2005b. Integration of agronomic practices and herbicides for sustainable weed management in a zero-till barley field pea rotation. Weed Technol. 19:190-196.

Blackshaw, R. E., G. P. Semach, and J. T. O'Donovan. 2000. Utilization of wheat seed rate to manage redstem filaree (*Erodium cicutarium*) in a zero-tillage cropping system. Weed Technol. 14:389-396.

Boyd, N. and R. Van Acker. 2004. Seed and microsite limitations to emergence of four annual weed species. Weed Sci. 52:571-577.

Buhler, D. D., R. G. Hartzler, and F. Forcella. 1997. Implications of weed seedbank dynamics to weed management. Weed Sci. 45:329-336.

Buhler, D. D., M. Liebman, and J. J. Obrycki. 2000. Theoretical and practical challenges to and IPM approach to weed management. Weed Sci. 48:274-280.

Burnside, O. C., R. S. Moomaw, F. W. Roeth, G. A. Wicks, and R. G. Wilson. 1986. Weed seed demise in soil in weed-free-corn (*Zea mays*) production across Nebraska. Weed Sci. 34:248-251.

Burnside, O. C., R. G. Wilson, S. Weisberg, and K. G. Hubbard. 1996. Seed longevity of 41 weed species buried 17 years in eastern and western Nebraska. Weed Sci. 44:74-86.

Cardina, J., C. P. Herms, and D. J. Doohan. 2002. Crop rotation and tillage system effects on weed seedbanks. Weed Sci. 50:448-460.

Cavers, P. B. 1995. Seed banks: Memory in soil. Can. J. Soil Sci. 75:11-13.

Chauvel, B., J. Gasquez, and H. Darmency. 1989. Changes of weed seed bank parameters according to species, time and environment. Weed Res. 29:213-219.

Chee-Sanford, J. C., M. M. Williams, A. S. Davis, and G. K. Sims. 2006. Do microorganisms influence seed-bank dynamics? Weed Sci. 54:575-587.

Clay, S. A., J. Kleinjan, D. E. Clay, F. Forcella, and W. Batchelor. 2005. Growth and fecundity of several weed species in corn and soybean. Agron. J. 97:294-302.

Clements, D. R., D. L. Benoit, S. D. Murphy, and C. J. Swanton. 1996. Tillage effects on weed seed return and seedbank composition. Weed Sci. 44:314-322.

Conn, J. S., K. L. Beattie, and A. Blanchard. 2006. Seed viability and dormancy of 17 weed species after 19.7 years of burial in Alaska. Weed Sci. 54:464-470.

Conn, J. S. and R. E. Deck. 1995. Seed viability and dormancy of 17 weed species after 9.7 years of burial in Alaska. Weed Sci. 43:583-585.

Conn, J. S. and M. L. Farris. 1987. Seed viability and dormancy of 17 weed species after 21 months in Alaska. Weed Sci. 35:524-528.

Cromar, H. E., S. D. Murphy, and C. J. Swanton. 1999. Influence of tillage and crop residue on postdispersal predation of weed seeds. Weed Sci. 47:184-194.

Davis, A. S. 2008. Weed seed pools concurrent with corn and soybean harvest in Illinois. Weed Sci. 56:503-508.

Davis, A. S., K. I. Anderson, S. G. Hallett, and K. A. Renner. 2006. Weed seed mortality in soils with contrasting agricultural management histories. Weed Sci. 54:291-297.

Davis, A. S. and M. Liebman. 2003. Cropping system effects on giant foxtail (*Setaria faberi*) demography: I. green manure and tillage timing. Weed Sci. 51:919-929.

Davis, A. S., K. A. Renner, E. C. Luschei, M. M. Williams II, C. L. Sprague, J. L. Lindquist, F. Forcella, J. Cardina, G. Kegode, and G. A. Johnson. 2005. Environmental factors affecting seed persistence of annual weeds across the U.S. Corn Belt. Weed Sci. 53:860-868.

Egley, G. H. and J. M. Chandler. 1978. Germination and viability of weed seeds after 2.5 years in a 50 year buried seed study. Weed Sci. 230-239.

Forcella, F. 1992. Prediction of weed seedling densities from buried seed reserves. Weed Res. 32:29-38.

Forcella, F., R. L. Benech Arnold, R. Sanchez, and C. M. Ghersa. 2000. Modeling seedling emergence. Field Crops Res. 67:123-139.

Freund R. J. and R. C. Littell. 2000. SAS System for Regression, Third Edition. Cary, N.C.: SAS Institute Inc**.**

Gallagher, R. S. and J. Cardina. 1998. Phytochrome-mediated amaranthus germination. I. Effect of seed burial and germination temperature. Weed Sci. 46:48-52.

Gallandt, E. R. 2006. How can we target the weed seedbank [electronic resource]. Weed Sci. 54:588-596.

Gallandt, E. R., E. P. Fuerst, and A. C. Kennedy. 2004. Effect of tillage, fungicide seed treatment, and soil fumigation on seed bank dynamics of wild oat (*Avena fatua*). Weed Sci. 52:597-604.

Gallandt, E. R., T. Molloy, R. P. Lynch, and F. A. Drummond. 2005. Effect of cover-cropping systems on invertebrate seed predation. Weed Sci. 53:69-76.

Grabe,D.F. 1970. Tetrazolium testing handbook for agricultural seeds. Contribution no. 29. Handbook on seed testing. Assoc. of Official Seed Analysts, Las Cruces, NM. Pp. 62.

Hanson, B. K., B. L. Johnson, R. A. Henson, and N. R. Riveland. 2008. Seeding rate, seeding depth, and cultivar influence on spring canola performance in the Northern Great Plains. Agron. J. 100:1339-1346.

Harker, K. N., R. E. Blackshaw, and G. W. Clayton. 2001. Timing of weed removal in field pea (*Pisum sativum*). Weed Technol. 15:277-283.

Harker, K. N., R. E. Blackshaw, and G. W. Clayton. 2008. Comparison of leafy and semileafless pea for integrated weed management. Weed Technol. 22:124-131.

Harker, K. N., G. W. Clayton, J. T. O'Donovan, R. E. Blackshaw, and F. C. Stevenson. 2004. Herbicide timing and rate effects on weed management in three herbicide-resistant canola systems. Weed Technol. 18:1006-1012.

Harker, K. N., G. W. Clayton, R. E. Blackshaw, J. T. O'Donovan, and F. C. Stevenson. 2003. Seeding rate, herbicide timing and competitive hybrids contribute to integrated weed management in canola (*Brassica napus*). Can. J. Plant Sci. 83:433-440.

Harker, K. N., T. K. Turkington, G. W. Clayton, J. T. O'Donovan, and R. B. Irvine. 2009. Integrating cropping systems with cultural techniques augments wild oat (*Avena fatua*) management in barley [electronic resource]. Weed Sci. 57:326-337.

Harrison, S. K., E. E. Regnier, and J. T. Schmoll. 2003. Postdispersal predation of giant ragweed (*Ambrosia trifida*) seed in no-tillage corn. Weed Sci. 51:955-964.

Holman, J. D., A. J. Bussan, B. D. Maxwell, P. R. Miller, and J. A. Mickelson. 2006. Persian darnel (*Lolium persicum*) fecundity response to spring wheat, canola, and sunflower interference. Weed Technol. 20:430-437.

Holmes, R. J. and R. J. Froud-Williams. 2005. Post-dispersal weed seed predation by avian and non-avian predators. Agric. Ecosyst. Environ. 105:23-27.

Hou, J. Q., E. J. Kendall, and G. M. Simpson. 1997. Water uptake and distribution in non-dormant and dormant wild oat (A*vena fatua* L.) caryopses. J. Exp. Bot. 48:683-692.

Hucl, P. 1998. Response to weed control by four spring wheat genotypes differing in competitive ability. Can. J. Plant Sci. 78:171-173.

Hulme, P. E. 1998. Post-dispersal seed predation: Consequences for plant demography and evolution. Perspect. Plant Ecol. Systemat. 1:32-46.

Jacob H., D. Minkey, R. Gallagher, and C. Borger. 2006. Variation in postdispersal weed seed predation in a crop field. Weed Sci. 54: 148-155.

Johnston, A. M., G. W. Clayton, G. P. Lafond, K. N. Harker, T. J. Hogg, E. N. Johnson, W. E. May, and J. T. McConnell. 2002. Field pea seeding management. Can. J. Plant Sci. 82:639-644.

Kremer, R. J. 1986. Antimicrobial activity of velvetleaf (*Abutilon theophrasti*) seeds. Weed Sci. 34:617-622.

Kremer, R. J. 1993. Management of weed seed banks with microorganisms. Ecol. Appl. 3:42-52.

Leeson, J. Y., A. G. Thomas, and L. M. Hall. 2002. 2001 Alberta weed survey of cereal, oilseed, and pulse crops. Saskatoon, SK: Agriculture and Agri-Food Canada Weed Survey Series Publ. 02-1. 263 p.

Leon, R. G. and M. D. K. Owen. 2004. Artificial and natural seed banks differ in seedling emergence patterns. Weed Sci. 52:531-537.

Levin, D. A. 1990. The seed bank as a source of genetic novelty in plants. Am. Nat. 135:563-572.

Lewis, J. 1973. Longevity of crop and weed seeds: Survival after 20 years in soil. Weed Res. 179-191.

Littell R. C., G. Milliken A., W. Stroup W., R. Wolfinger D., and O. Schabenberger. 2006. SAS for Mixed Models: Second Edition. Cary, N.C: SAS Institute Inc.

Lutman, P. J. W. 2002. Estimation of seed production by S*tellaria media*, S*inapis arvensis* and *Tripleurospermum inodorum* in arable crops. Weed Res. 42:359-369.

Lutman, P. J. W., G. W. Cussans, K. J. Wright, B. J. Wilson, G. M. Wright, and H. M. Lawson. 2002. The persistence of seeds of 16 weed species over six years in two arable fields. Weed Res. 42:231-241.

Mallows, C. L. 1973. Some comments on CP. Technometrics 15:661-675.

Marino, P. C., K. L. Gross, and D. A. Landis. 1997. Weed seed loss due to predation in michigan maize fields. Agric. Ecosyst. Environ.66:189-196.

Marino, P. C., P. R. Westerman, C. Pinkert, and W. van der Werf. 2005. Influence of seed density and aggregation on post-dispersal weed seed predation in cereal fields. Agric. Ecosyst. Environ.106:17-25.

Martin, S. G., R. C. Van Acker, and L. F. Friesen. 2001. Critical period of weed control in spring canola. Weed Sci. 49:326-333.

Martinson, K., K. Spokas, D. Archer, J. Wiersma, B. Durgan, and F. Forcella. 2007. An emergence model for wild oat (A*vena fatua*). Weed Sci. 55:584-591.

Masin, R., M. C. Zuin, S. Otto, and G. Zanin. 2006. Seed longevity and dormancy of four summer annual grass weeds in turf. Weed Res. 46:362-370.

Mauchline, A. L., S. J. Watson, V. K. Brown, and R. J. Froud-Williams. 2005. Post-dispersal seed predation of non-target weeds in arable crops. Weed Res. 45:157-164.

Maxwell, B. D., R. G. Smith, and M. Brelsford. 2007. Wild oat (*Avena fatua*) seed bank dynamics in transition to organic wheat production systems. Weed Sci. 55:212-217.

Menalled, F. D., P. C. Marino, K. A. Renner, and D. A. Landis. 2000. Post-dispersal weed seed predation in Michigan crop fields as a function of agricultural landscape structure. Agric. Ecosyst. Environ.77:193-202.

Menalled, F. D., R. G. Smith, J. T. Dauer, and T. B. Fox. 2007. Impact of agricultural management on carabid communities and weed seed predation. Agric. Ecosyst. Environ. 118:49-54.

Mickelson, J. A. and W. E. Grey. 2006. Effect of soil water content on wild oat (A*vena fatua*) seed mortality and seedling emergence. Weed Sci. 54:255-262.

Miller, S. D. and J. D. Nalewaja. 1990. Influence of burial depth on wild oats (*Avena fatua*) seed longevity. Weed Technol.4:514-517.

Mitschunas, N., M. Wagner, and J. Filser. 2006. Evidence for a positive influence of fungivorous soil invertebrates on the seed bank persistence of grassland species [electronic resource]. J. Ecol. 94:791-800.

Murphy, S. D., D. R. Clements, S. Belaoussoff, P. G. Kevan, and C. J. Swanton. 2006. Promotion of weed species diversity and reduction of weed seedbanks with conservation tillage and crop rotation. Weed Sci. 54:69-77.

Myers, S. P., M. E. Foley, and M. B. Nichols. 1997. Developmental differences between germinating after-ripened and dormant excised *Avena fatua* L. embryos. Annals of Botany 79:19-23.

Norris, R. F. 2007. Weed fecundity: Current status and future needs. Crop Protect. 26:182-188.

O'Donovan, J. T., R. E. Blackshaw, K. N. Harker, and G. W. Clayton. 2006. Wheat seeding rate influences herbicide performance in wild oat (*Avena fatua* L.) [electronic resource]. Agron. J. 98:815-822.

O'Donovan, J. T., R. E. Blackshaw, K. N. Harker, G. W. Clayton, and R. McKenzie. 2005. Variable crop plant establishment contributes to differences in competitiveness with wild oat among cereal varieties. Can. J. Plant Sci. 85:771-776.

O'Donovan, J. T., R. E. Blackshaw, K. N. Harker, G. W. Clayton, J. R. Moyer, L. M. Dosdall, D. C. Maurice, and T. K. Turkington. 2007. Integrated approaches to managing weeds in spring-sown crops in western Canada. Crop Protect. 26:390-398.

O'Donovan, J. T., K. N. Harker, G. W. Clayton, and L. M. Hall. 2000. Wild oat (*Avena fatua*) interference in barley (*Hordeum vulgare*) is influenced by barley variety and seeding rate. Weed Technol. 14:624-629.

O'Donovan, J. T., K. N. Harker, G. W. Clayton, L. M. Hall, J. Cathcart, K. L. Sapsford, F. A. Holm, and K. Hacault. 2007. Volunteer barley interference in spring wheat grown in a zero-tillage system. Weed Sci. 55:70-74.

O'Donovan, J. T., K. N. Harker, G. W. Clayton, J. C. Newman, D. Robinson, and L. M. Hall. 2001. Barley seeding rate influences the effects of variable herbicide rates on wild oat. Weed Sci. 49:746-754.

O'Donovan, J. T., J. C. Newman, K. N. Harker, R. E. Blackshaw, and D. W. McAndrew. 1999. Effect of barley plant density on wild oat interference, shoot biomass and seed yield under zero tillage. Can. J. Plant Sci. 79:655-662.

O'Donovan, J. T., J. C. Newman, K. N. Harker, and G. W. Clayton. 2004. Crop seeding rate influences the performance of variable herbicide rates in a canola-barley-canola rotation. Weed Technol. 18:733-741.

O'Donovan, J. T., T. K. Turkington, N. Z. Lupwayi, K. N. Harker, G. W. Clayton, and C. A. Grant. 2008. Effect of nitrogen rate and placement and seeding rate on barley productivity and wild oat fecundity in a zero tillage system. Crop Sci. 48:1569-1574.

Ominski, P. D., M. H. Entz, and N. Kenkel. 1999. Weed suppression by *Medicago sativa* in subsequent cereal crops: A comparative survey. Weed Sci. 47:282-290.

O'Rourke, M. E., A. H. Heggenstaller, M. Liebman, and M. E. Rice. 2006. Post-dispersal weed seed predation by invertebrates in conventional and low-external-input crop rotation systems. Agric. Ecosyst. Environ. 116:280-288.

Sagar, G. R. and A. M. Mortimer. 1976. An approach to the study of the population dynamics of plants with special reference to weeds. Appl. Biol. 1:1-47.

Schutte, B. J., J. Cardina, K. A. Renner, and A. S. Davis. 2008. Maternal and burial environment effects on seed mortality of velvetleaf (*Abutilon theophrasti*) and giant foxtail (*Setaria faberi*). Weed Sci. 56:834-840.

Schweizer, E. E. and R. L. Zimdahl. 1984. Weed seed decline in irrigated soil after six years of continuous corn *(Zea mays*) and herbicides. Weed Sci. 32:76-83.

Sharma, M. P. and W. H. Vanden Born. 1978. The biology of Canadian weeds. 27. *Avena fatua* L. Can. J. Plant Sci. 141-157.

Shirtliffe, S. J., M. H. Entz, and R. C. Van Acker. 2000. *Avena fatua* development and seed shatter as related to thermal time. Weed Sci. 48:555-560.

Simpson R. L., M. A. Leck, and V. T. Parker. 1989. Seed banks: General concepts and methodological issues. Pages 3-8 *In* M. A. Leck, V. T. Parker and R. L. Simpson, eds. Ecology of Soil Seed Banks. San Diego, California, U.S.A.: Academic Press, Inc.

Sosnoskie, L. M., C. P. Herms, and J. Cardina. 2006. Weed seedbank community composition in a 35-yr-old tillage and rotation experiment. Weed Sci. 54:263-273.

Swanton, C. J. and B. D. Booth. 2004. Management of weed seedbanks in the context of populations and communities. Weed Technol. 1496-1502.

Swanton, C. J., B. D. Booth, K. Chandler, D. R. Clements, and A. Shrestha. 2006. Management in a modified no-tillage corn-soybean-wheat rotation influences weed population and community dynamics. Weed Sci. 54:47-58.

Swanton, C. J., R. H. Gulden, K. Chandler, and K. J. Mahoney. 2008. Integrated weed management: Knowledge-based weed management systems [electronic resource]. Weed Sci. 56:168-172.

Swanton, C. J. and S. D. Murphy. 1996. Weed science beyond the weeds: The role of integrated weed management (IWM) in agroecosystem health. Weed Sci. 44:437-445.

Telewski, F. W. and J. A. D. Zeevaart. 2002. The 120-yr period for Dr. Beal's seed viability experiment. Am. J. Bot. 89:1285-1288.

Thompson, K., J. P. Bakker, R. M. Bekker, and J. G. Hodgson. 1998. Ecological correlates of seed persistence in soil in the north-west European flora. J. Ecol. 86:163-169.

Toole, E. H. and E. Brown. 1946. Final results of the Duvel buried seed experiment. J. Ag. Res. 72:201-210.

Van Delden, A., L. A. P. Lotz, L. Bastiaans, A. C. Franke, H. G. Smid, R. M. W. Groeneveld, and M. J. Kropff. 2002. The influence of nitrogen supply on the ability of wheat and potato to suppress *Stellaria media* growth and reproduction. Weed Res. 42:429-445.

Van Mourik, T. A., T. J. Stomph, and A. J. Murdoch. 2005. Why high seed densities within buried mesh bags may overestimate depletion rates of soil seed banks. J. Appl. Ecol. 42:299-305.

Watson, P. R., D. A. Derksen, and R. C. Van Acker. 2006. The ability of 29 barley cultivars to compete and withstand competition. Weed Sci. 54:783-792.

Webster, T. M., J. Cardina, and A. D. White. 2003. Weed seed rain, soil seedbanks, and seedling recruitment in no-tillage crop rotations. Weed Sci. 51:569-575.

Westerman, P. R., A. Hofman, L. E. M. Vet, and W. van der Werf. 2003a. Relative importance of vertebrates and invertebrates in epigeaic weed seed predation in organic cereal fields. Agric. Ecosyst. Environ. 95:417-425.

Westerman, P. R., J. S. Wes, M. J. Kropff, and W. Van der Werf. 2003b. Annual losses of weed seeds due to predation in organic cereal fields. J. Appl. Ecol. 40:824-836.

White, S. S., K. A. Renner, F. D. Menalled, and D. A. Landis. 2007. Feeding preferences of weed seed predators and effect on weed emergence. Weed Sci. 55:606-612.

Xue, Q. W. and R. N. Stougaard. 2002. Spring wheat seed size and seeding rate affect wild oat demographics. Weed Sci. 50:312-320.

Zhang, J., A. S. Hamill, I. O. Gardiner, and S. E. Weaver. 1998. Dependence of weed flora on the active soil seedbank. Weed Res. 38:143-152.

Zhang J., F. A. Drummond, M. Liebman, and A. Hartke. 1997. Insect predation of seeds and plant population dynamics. Orono, ME: Maine Agricultural and Forest Experiment Station. 28 p.

Chapter 4. Seasonal emergence and survival patterns of wild oat (*Avena fatua* L.) under integrated weed management systems in central Alberta

4.1. Introduction

Wild oat (*Avena fatua* L.) is an economically significant grass weed across the Canadian Prairies. The cost of managing wild oat in spring wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.) and canola (*Brassica napus* L.) crops in western Canada can exceed $500 million dollars annually (Leeson et al. 2006). Herbicides have been effectively used to eliminate or minimize losses in crop yield and quality from wild oat (O'Donovan et al. 2003; Wille et al. 1998). However, for many growers an overreliance on herbicides has resulted in repeated applications of herbicides with the same mode of action and the selection of herbicide resistant weed biotypes (Beckie 2007).

Resistance to common graminicides include both group 1 (acetyl- CoA-carboxylase (ACCase) inhibitor) and Group 2 (acetolactate synthase (ALS) inhibitor) modes of action. In a field survey of herbicide resistant weeds in Alberta, 11% and 13% of fields contained ACCase inhibitor and ALS herbicide resistant wild oat (Beckie 2004). Coupling cultural weed management practices with less frequent selective herbicide use provides an opportunity to minimize the evolution and spread of herbicide resistant weeds (Beckie 2007). Consequently, mitigating the evolution of herbicide resistance in wild oat populations will require integrating various cultural weed management practices with alternative herbicide use to ensure cropping systems remain economically and environmentally sustainable.

Robust weed management strategies can be achieved by integrating numerous cultural management practices to promote crop competition and minimize weed establishment. IWM strategies within canola cropping systems that combine a competitive canola cultivar with increased seeding rate and early weed removal can improve canola yields and reduce weed biomass (Harker et al. 2003). Similarly, within a direct seeded spring wheat–canola rotation, a combination of early seeding, increased crop seeding rates, and spring-banded fertilizer reduced weed biomass and weed seed banks while maintaining high crop yields (Blackshaw et al. 2005). Integrating agronomic practices with chemical control measures have been successful in reducing wild oat biomass, seed production and seed bank densities (Blackshaw et al. 2008; Harker et al. 2009; O'Donovan et al. 2008). O'Donovan et al. (2006) reported less wild oat biomass and seed in the soil seed bank when wild oat herbicides were applied to wheat seeded at 150 kg ha^{-1} than at 75 kg ha^{-1}.

The time of weed emergence relative to crop emergence is also important for considering potential crop yield loss (O'Donovan et al. 1985). Generally, when weeds emerge with or prior to the crop, greater crop yield loss can occur (Bosnic and Swanton 1997; O'Donovan et al. 1985; Willenborg et al. 2005b); therefore, early seeding (Chen et al. 2005; Clayton et al. 2004; Kirkland and Johnson 2000) and pre-emergent weed control (Johnson et al. 2002) can maximize weed control and grain yield. O'Donovan et al. (1985) reported a 3% reduction in crop yield for each day that wild oat emerged prior to wheat or barley. Late emerging weed seedlings typically have a minimal impact on crop yield (Bosnic and Swanton 1997; Swanton et al. 2008). While yield responses to early weed removal has been consistently reported (Harker et al. 2001; Harker et al. 2008; Martin et al. 2001; O'Donovan et al. 1985; Willenborg et al. 2005a), the implication for weed populations are less clear. In western Canada, there are no reports of the success of weed cohorts that follow a herbicide application and their role in replenishing the seed bank.

Timing control measures to optimize weed control and maximize yield requires knowledge of the time and extent weeds emerge from the soil seed bank. Dormancy, germination and emergence are three important biological processes that regulate wild oat soil seed banks. Wild oat seed germination and emergence are largely influenced by the induction and release of primary and secondary dormancy. The level of dormancy within a wild oat seed population is influenced by a range of environmental and genetic interactions. For example, a broad range of dormancy phenotypes ranging from nondormant to extremely dormant can be expressed within a genetically distinct wild oat seed population (Adkins et al. 1986). Furthermore, an extensive range of environmental conditions influence the level and ability of a wild oat seed to be released and induced from a dormant state including ambient air temperature (Sawhney and Naylor 1980), soil moisture (Sawhney and Naylor 1982) and photoperiod (Armstrong and Adkins 1998). A period of after-ripening under warm, dry conditions is necessary for wild oat seeds to overcome primary dormancy (Myers et al. 1997). Wild oat seeds that experience a prolonged period of after-ripening may enter and re-enter secondary dormancy (Hou et al. 1997). Secondary dormancy cycling can permit wild oat seedlings to emerge intermittently, allowing some seedlings to escape early in-crop control efforts. Efforts to develop predictive emergence models for wild oat within western Canada will require additional information on factors that regulate wild oat seedling emergence across geographies and within diverse cropping systems.

Empirical emergence models have been developed using thermal time or GDD, using mean accumulated daily air or soil temperatures (De Corby et al. 2007; Dexter et al. 2010; Lawson et al. 2006). HTT (hydrothermal time) models have been successful in predicting and modeling weed emergence since they incorporate soil water potential and soil temperature (Forcella et al. 2000; Martinson et al. 2007). Wild oat seedling emergence has been correlated with soil GDD and HTT (Bullied et al. 2003; Martinson et al. 2007). HTT models can provide a more accurate prediction of emergence especially when soil moisture conditions are limiting (Martinson et al. 2007).

The objective of this study was to determine the emergence period of wild oat as a function of growing degree days in central Alberta and to establish the impact IWM practices have on wild oat seedling emergence and survivorship. Additional information on the emergence period of wild oat and the capability of wild oat seedlings to contribute to the wild oat seed bank can improve our understanding on the efficacy of weed control measures implemented in IWM systems.

4.2. Materials and Methods

4.2.1. Site Description

Four seven-year cropping systems trials were established at Agriculture and Agri-Food Canada (AAFC) locations across western Canada (Beaverlodge, AB, Brandon, MB, Fort Vermilion, AB and Lacombe, AB) (Harker et al. 2009). The initial study quantified the effects of combining crop rotation, barley cultivar and barley seeding rate under reduced and full post emergent wild oat herbicide rates on barley grain yield and biomass as well as wild oat density, biomass and seed production.

For ease of discussion and consistency, “low management” (i.e. Short-1X-Cont) will be used to describe the short cultivar, 1X barley seeding rate and continuous barley rotation and “high management” (i.e. Tall-2X-Rot) will define the tall cultivar, 2X barley seeding rate and diversified barley rotation treatment. In conjunction with the initial study, data were collected at Lacombe, Alberta (52°27' N, 113°45' W) in 2006 and 2007 to characterize wild oat seedling emergence and their contribution to the wild oat seed bank within integrated weed management systems. The soil at Lacombe is an Orthic Black Chernozem (Typic Haplustoll) with a loam soil texture (51% sand, 30% silt and 19% clay) pH of 6.6 and 7.8% organic matter.

Plots were direct seeded with a ConservaPak[1] air seeder with 1 cm wide knife openers and 23 cm row spacing (Table 4.1.). Plot size was 3 by 15 m. Nitrogen, phosphorous, potassium and sulfur fertilizers were side banded at seeding using soil test recommendations. Short (Vivar) and tall (AC Lacombe) barley varieties were seeded at a 3 cm depth under a normal seeding rate of 200 seeds m^{-2} or a doubled rate of 400 seeds m^{-2}. Canola (Invigor 5020) was planted at a recommended rate of 150 seeds m^{-2} at a depth of 1 cm. Seeding rates were calculated using thousand kernel weights.

An application of glyphosate[2] (450 to 900 g ae ha^{-1}) was applied in the spring of 2006 and 2007 to control early emerging annual weeds and winter annuals. In 2006, plots with barley received either a quarter, half or full application of fenoxaprop-p-ethyl[3] (23, 46 or 93 g ai ha^{-1}) tank mixed with quinclorac/thifensulfuron/tribenuron[4] (50 /15/15 g ai ha^{-1}) at the three- to four-leaf stage (Table 4.1.). Similarly, glufosinate-tolerant canola received either a quarter,

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[1] Direct-seeding equipment, Conserva Pak Air Seeder, Model CP 129A, Conserva Pak Seeding Systems/Division of Vale Farms Ltd., P.O. Box 1420, Indian Head, SK S0G 2K0, Canada.

[2] Glyphosate, Roundup, Roundup Transorb, or Roundup WeatherMax, Monsanto Canada Inc., 67 Scurfield Blvd., Winnipeg, MB R3Y 1G4, Canada.

[3] Fenoxaprop-p-ethyl, Puma Super 120, Bayer Crop Science Inc., 100, 3131-114Ave. S.E., Calgary, AB T2Z 3X2, Canada.

[4] Quinclorac/thifensulfuron/tribenuron, DuPont Canada Inc. 4444 72 Ave. S.E., Calgary, AB T2C 2C1, Canada.

half or full application of glufosinate[5] (125, 250 or 500 g ai ha^{-1}) and a tank mix of clethodim[6] (17, 34 or 67 g ai ha^{-1} plus adjuvant[7] at 0.5% v/v) at the three-leaf stage (Table 4.1.). In 2007, barley received an application of imazamethabenz[8] (125, 250 or 500 g ai ha^{-1}) tank mixed with florasulam/MCPA[9] ester (5/240 g ai ha^{-1}) (Table 4.1.). Herbicides were applied at 275 kPa in 93.5 L ha^{-1} of water.

4.2.2. Wild oat seedling emergence

Wild oat seedling emergence was measured weekly in Lacombe in 2006 and 2007 from May until July in three permanent 0.25m^{-2} quadrats, randomly placed in each plot following seeding. Newly emerged wild oat seedlings were counted and denoted with an avian leg band. Each week a different color/pattern of avian leg band was used to characterize the emergence periods. Emergence counts ceased in the beginning of July to preserve the integrity of the plots. Wild oat emergence counts were divided into two time periods: (1) emergence up to

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[5] Glufosinate, Liberty, Bayer Crop Science Inc., 100, 3131-114Ave. S.E., Calgary, AB T2Z 3X2, Canada.

[6] Clethodim, Select, Arysta LifeScience Canada Inc., 998, 105-150 Crowfoot Cres. N.W., Calgary, AB T3G 3T2, Canada.

[7] Adjuvant, Amigo, Bayer Crop Science Inc., 100, 3131-114 Ave. S.E., Calgary, AB T2Z 3X2, Canada.

[8] Imazamox/imazethapyr, Odyssey, BASF Canada Inc., 345 Carlingview Dr., Toronto, ON M9W 6N9, Canada.

[9] Florasulam/MCPA, Frontline, Dow AgroSciences Canada, 2100, 450 1st St. S.W., Calgary, AB T2P 5H1, Canada.

and including the day of post-emergent herbicide application and (2) emergence following post-emergent herbicide application.

Avian leg bands were removed from seedlings that effectively succumbed to the post-emergent herbicide application or failed to produce seed prior to harvest. Consequently, the remaining seedlings were deemed successful survivors in their ability to contribute seeds into the seed bank. Similar to emergence counts, seedling success was segmented into two time periods: (1) seedlings that survived from prior to and including the day of post-emergent herbicide application and (2) seedlings that survived post herbicide application (i.e. seedlings not exposed to the herbicide application).

Precipitation (rainfall) and daily air temperature data for 2006 and 2007 were collected from Environment Canada using the Lacombe, AB weather station. Air temperature data collected from the Environment Canada weather station was used to calculate daily growing degree days (GDD) for 2006 and 2007. Daily GDD measurements were calculated from January 1 of each year until emergence counts ceased. Cumulative GDD were calculated for each year using the following equation:

$$GDD=\sum[(T_{max}+T_{min})/2- T_{base}] \qquad [1]$$

where, T_{max} is the daily maximum air temperature, T_{min} is the daily minimum air temperature and T_{base} is the base temperature (0°C) for wild oat growth and development (Shirtliffe et al. 2000; Willenborg et al. 2005b). Daily GDD values that were negative were changed to 0.

4.2.3. Statistical Analyses

4.2.3.1. Emergence Timing

The density of wild oat seedlings was expressed as a cumulative percentage of total wild oat emergence during weekly observations. GDD were summed over each emergence period in 2006 and 2007 to obtain an accumulated weekly GDD total. The emergence response to GDD was fitted to a log-logistic curve using NLIN in SAS. The model fitted was:

$$y = \mathrm{C} + \frac{\mathrm{D - C}}{1 + \exp[\mathrm{b}(\log(x) - \log(\mathrm{E50}))]} \qquad [2]$$

where, y is cumulative percent emergence of wild oat, x is the cumulative GDD, C represents the lower asymptote, $D - C$ represents the upper asymptote (maximum emergence), E_{50} is the x value (GDD) at the midpoint or inflection point of the curve and b is the slope (Burke et al. 2005; Seefeldt et al. 1995). The lower asymptote of the curve was constrained at zero, as no emergence occurred at 0 GDD. To test if the 2006 and 2007 curves were parallel, curves were analyzed systematically for common C and D, common E_{50} and common b using the lack-of-fit F-test at the 0.05 level of significance (Seefeldt et al. 1995). A coefficient of determination (R^2) was calculated using the residual sum of squares value as described in Kvalseth (1985). The log-logistic model in Equation [2] is similar to the emergence model used to characterize volunteer canola (Lawson et al. 2006), volunteer wheat (De Corby et al. 2007) and volunteer flax (Dexter et al. 2010;

emergence periodicity; therefore, a similar log-logistic model was chosen for its simplicity, accuracy in fitting data and biological application to weed growth.

4.2.3.2. Seedling Emergence and Survivorship

A test for normality and heterogeneity on the residuals was performed using PROC GLIMMIX (Littell et al. 2006). Data for wild oat emergence and seedling survivorship from both prior to and post herbicide application had a right skewed distribution and heterogeneous variances; therefore, logarithmic transformations ($\log_{10}(x+1)$) were performed. Data were analyzed using PROC MIXED of SAS (Littell et al. 2006) whereby year and replicate were treated as random effects. The significance of main effects (crop rotation, seeding rate, barley variety and herbicide rate) and their interactions were determined for each variable (data not shown). Discussion will focus on the pre-planned contrasts conducted on specific treatment differences and related to comparisons referred to in Harker et al. (2009), whereby contrasts of fixed effects were corrected using Bonferroni adjustments and considered significant at $P<0.004$.

4.3. Results and Discussion

4.3.1. Emergence Timing

4.3.1.1. Weather Data

Weather conditions in Lacombe during the 2006 growing season were more consistent with the 30 year long term average compared to 2007 (Table 4.2.). Mean monthly temperatures during the 2006 and 2007 growing seasons were consistent with mean temperatures from 1971 to 2000. In the spring of 2007, soils were saturated as a result of significant amounts of rainfall during May and June.

4.3.1.2. Time of Emergence

Using a base temperature of 0°C, GDD provided a simple and effective measurement of thermal time for wild oat emergence during the 2006 and 2007 growing season (Figure 4.1.). The emergence periodicity of wild oat was similar between 2006 and 2007 ($P=0.9938$) despite higher accumulations of precipitation in 2007. Early season moisture in 2007 may have provided slightly more favorable conditions early in May and June to release secondary dormancy and permit germination slightly earlier than in 2006. Wild oat seeds respond favorably to additional moisture, whereby maximum seedling emergence is reached when soil moistures range between 50 to 75% field capacity (Sharma et al. 1976).

The wild oat population reached 50% emergence at 537 and 509 GDD in 2006 and 2007, respectively, and 90% emergence at 785 and 749 GDD in 2006 and 2007, respectively (Table 4.3.). Extended periods of emergence may be a function of secondary dormancy release (Benech-Arnold et al. 2000) and/or favorable conditions for germination among seed microsites (Boyd and Van Acker 2004). Bullied et al. (2003) observed 50% wild oat emergence at 511 and 417 GDD (T_{base} 0°C) in conventional and conservation tillage fields in Manitoba, respectively; however, soil moisture was limiting during this study. Martinson et al. (2007) reported 50% wild oat emergence in Fargo, ND and Crookston, MN at

245 GDD, but since a base temperature of 1°C was used in the GDD calculations, data from this emergence model cannot be directly compared. Wild oat emergence is more prolonged than weeds like volunteer canola and volunteer wheat, which rapidly emerge in the growing season prior to seeding annual crops. Lawson et al. (2006) reported 50% volunteer canola emergence at $\leq$132 GDD (T_{base} = 5°C). Similarly, the E_{50} for volunteer spring wheat was calculated at $\leq$235 GDD (T_{base} =0°C) (De Corby et al. 2007).

Both GDD (Bullied et al. 2003; Martinson et al. 2007) and HTT (Martinson et al. 2007) models have been used to characterize wild oat emergence; however, HTT models that use both soil temperature and soil moisture tend to be more accurate in successfully predicting wild oat emergence over GDD models (Martinson et al. 2007). Developing a HTT emergence model of wild oat in western Canada would be beneficial for growers and agricultural professionals to predict wild oat emergence and assist with implementing weed management practices.

4.3.2. Wild Oat Emergence

Main effects were significant in 2006 and 2007, but interactions were not significant (data not shown). Wild oat emergence from 2006 and 2007 reflects five and six years, respectively, of cumulative IWM techniques at Lacombe, Alberta. Emergence was divided based on the number of seedlings that emerged prior to and following post-emergent herbicide application. The post-emergent herbicide applications in barley and canola during 2006 occurred at 557 GDD and

573 GDD, respectively, corresponding to 53% and 55% cumulative wild oat emergence (Figure 4.1.). In 2007, post-emergent herbicide applications occurred at 566 GDD in barley at 57% cumulative wild oat emergence.

4.3.2.1. Wild Oat Emergence Prior to Post-Emergent Herbicide

4.3.2.1.1. Lacombe 2006 and 2007

High management strategies significantly reduced the amount of wild oat seedlings prior to herbicide application in 2006 and 2007 (Figure 4.2.). The impact of tall barley cultivars ($P \leq 0.0020$) and crop rotation ($P \leq 0.0002$) were highly effective at the quarter herbicide rate. Using optimal agronomic practices with quarter herbicide rates in 2006 and 2007, respectively, reduced wild oat emergence from 800 and 819 plants m^{-2} in the Short-1X-Cont treatment to 31 and 77 plants m^{-2} in the Tall-2X-Rot treatment. In 2006, with the exception of the Short-2X-Cont treatment, all remaining Cont and Rot treatments were significantly more competitive than the Short-1X-Cont treatment. Using high management strategies under the quarter herbicide rate also resulted in less wild oat emerging than using low management strategies with a half herbicide rate ($P \leq 0.0007$). No statistically significant differences were detected between the low management strategy (Short-1x-Cont) at the full herbicide rate and high management strategy (Tall-2x-Rot) at the quarter herbicide rate ($P \leq 0.4889$).

At half and full herbicide rates, crop rotation was the most significant agronomic practice ($P<0.0001$); whereby, all treatments in the Rot treatments were significant from the Short-1X-Cont treatment. In 2007, all treatments within the full herbicide rate had significantly fewer wild oats emerging than from the Short-1x-Cont. No significant difference was detected in 2006 between the Tall-2x-Rot treatment at the half herbicide rate and the Short-1x-Cont treatment at the full rate ($P=0.8304$), but in 2007, significantly less wild oat emergence occurred using high management strategies with half herbicide rate compared to low management strategies at full herbicide rate ($P<0.0001$).

4.3.2.2. Wild Oat Emergence Following Post-Emergent Herbicide

The magnitude of wild oats emerging subsequent to post-emergent herbicide application was noticeably less than the number of wild oats that emerged prior to herbicide application, as represented by the emergence model (Figure 4.1.). The success of high management strategies was reflected in the emergence of wild oat following the application of post-emergent herbicides across all three rate structures.

4.3.2.2.1. Lacombe 2006 and 2007

Across herbicide rates in 2006 and 2007, combining all three optimal agronomic practices (i.e. tall barley cultivar, higher barley seeding rate and diverse crop rotation) were influential in reducing the amount of late emerging wild oat seedlings (Figure 4.3.). At the quarter herbicide rate, using a diverse crop rotation ($P<0.0001$) had the greatest impact on reducing wild oat seedling emergence. In 2007, using a tall barley cultivar ($P=0.0001$) also resulted in significantly fewer wild oat seedlings. Implementing high management strategies at the quarter herbicide rate in 2006 and 2007 reduced seedling emergence from

239 and 341 plants m^{-2} at the Short-1X-Cont treatment to 33 and 41 plants m^{-2} at the Tall-2X-Rot treatment, respectively. In 2006 there was no significant difference between the amount of wild oat seedlings in the high management system at the quarter herbicide rate and low management system at the half herbicide rate ($P=0.0087$). In 2007, significantly fewer wild oat seedlings emerged in the high management treatment at a quarter herbicide rate (41 plants m^{-2}) than in the low management system at half herbicide rate (230 plants m^{-2}; $P<0.0001$).

At the half herbicide rate, crop rotation was the main factor reducing wild oat emergence ($P<0.0001$). All treatments within Rot had significantly fewer wild oat seedlings than the Shot-1X-Cont treatment, whereas in the Cont treatment only Tall-1X-Cont had significantly fewer. In 2006, no significant difference in the amount of emergence occurred between the high management treatment in the half herbicide rate versus the low management treatment at full herbicide rate ($P=0.6821$). In 2007, using high management with a half herbicide rate (10 plants m^{-2}) resulted in significantly less wild oat seedlings than a full rate of herbicide with low management (53 plants m^{-2}; $P<0.0001$).

Diverse crop rotation ($P\leq0.0010$) resulted in less wild oat emergence at the full herbicide rate in 2006 and 2007. In 2007, barley cultivar ($P<0.0001$) also had a significant impact on reducing wild oat seedling emergence. In general, Rot treatments under the full herbicide rate significantly reduced wild oat seedling emergence compared to the Shot-1X-Cont treatment.

The impact of using optimal agronomic practices to enhance crop competitiveness with wild oat is consistent with earlier research (Harker et al.

2003; O'Donovan et al. 2000; O'Donovan et al. 2004; Zand and Beckie 2002). Adopting higher barley seeding rates and using tall barley cultivars can reduce wild oat competition and enhanced crop competitiveness; for example, barley yield loss can be reduced from 20 to 14% by enhancing barley plant stands from 150 to 250 plants m^{-2} in the presence of 50 wild oat plants m^{-2} (O'Donovan et al. 1999). Furthermore, the incorporation of a vigorous hybrid canola in the rotation can minimize wild oat competition (Zand and Beckie 2002) and provide diversity in post-emergent herbicide application timing and modes of action (Anderson 2003). Combining these agronomic practices provides a system that enhances crop health and crop competition with weeds and delays the selection for herbicide resistance (Harker et al. 2009).

4.3.3. Wild Oat Seedling Survivorship

Main effects were significant, but interactions were not significant in 2006 and 2007 (data not shown). The number of wild oat seedling survivors reflects the number of plants that contributed to the wild oat seed bank. Survivors from prior to the herbicide application were generally seedlings that escaped or survived the herbicide application. Survivors from post herbicide application would have not received the herbicide application; therefore, their reproductive success is based on their ability to compete for resources (i.e. light, water, nutrients) late in the growing season and the competitiveness of the crop as a result of the treatments.

In general, the proportion of survivorship was high across all herbicide rates, averaging between 56% and 80% in 2006 and 2007, respectively. The efficacy of herbicide rates may have been compromised by adverse weather conditions immediately prior or following application. The extent of wild oat seedlings surviving herbicide application in 2007 appeared greater than in 2006, ranging from 54% to 93% survivorship across all herbicide rates. The excessive precipitation during May and June of 2007 (Table 4.2.) may have resulted in less than ideal conditions for implementing post-emergent herbicide applications or reduced late season crop competition.

4.3.3.1. Wild oat Seedling Survivorship Prior to Post-emergent Herbicide

4.3.3.1.1. Lacombe 2006 and 2007

High management strategies were effective across all herbicide rates in reducing the number of successful wild oat seedlings that emerged prior to the application of a post-emergent herbicide (Figure 4.4.). In 2006 and 2007, crop rotation consistently reduced the number of wild oat seedling survivors ($P \leq 0.0018$). In 2007, barley cultivar was also ($P=0.0074$) a significant wild oat management strategy. Using Tall-2X-Rot over Short-1X-Cont management reduced the number of wild oat seedling survivors from 590 and 680 plants m^{-2} to 13 and 72 plants m^{-2} in 2006 and 2007, respectively. Applying high management strategies with quarter herbicide rates was more effective in reducing the number of wild oat seedling survivors than low management strategies used with half herbicide rates ($P \leq 0.0040$). In both years, wild oat seedling survivorship was not significantly different between high management at quarter herbicide rate and low management at full herbicide rates.

At the half and full herbicide rates, crop rotation was the only agronomic practice that resulted in fewer wild oat seedling survivors ($P<0.0001$). All Rot treatments had significantly fewer wild oat seedling survivors compared to the Short-1X-Cont treatment. Within the full herbicide rate treatments, all treatments but the Short-2X-Cont had reduced the number of wild oat seedling survivors compared to Short-1X-Cont. In 2006 and 2007, the number of seedlings surviving under the full herbicide rate between low and high management systems was reduced from 19 and 69 plants m^{-2} to 1 and 5 plants m^{-2}, respectively. In 2007, high management systems incorporated with half herbicide rates (9 plants m^{-2}) led to significantly fewer wild oats survivors than low management at full herbicide rate (69 plants m^{-2}; $P=0.0004$). In 2006, no significant difference in the number of wild oat seedling survivors occured between the high management system at half herbicide rate and low management at full herbicide rate ($P=0.3844$).

4.3.3.2. Wild Oat Seedling Survivorship Following Post-Emergent Herbicide

4.3.3.2.1. Lacombe 2006 and 2007

High management treatments remained effective in reducing the number of wild oat seedling survivors that emerged following a post-emergent herbicide in 2006 and 2007 (Figure 4.5.). Crop rotation ($P=0.0009$) was the most effective management strategy under the quarter herbicide rate in 2006. Similarly, in 2007, crop rotation ($P<0.0001$) and barley cultivar ($P=0.0008$) significantly reduced the number of wild oat seedling survivors under the quarter herbicide rate. In 2006 and 2007, the Tall-2X-Rot treatment had significantly fewer wild oat seedling survivors compared to the Short-1X-Cont treatment, from 100 and 202 plants m^{-2} to 21 and 24 plants m^{-2}, respectively. In 2006, there was no significant difference in the number of wild oat seedling survivors within the high management system at quarter herbicide rate than the low management system at half herbicide rate ($P=0.0126$) or full herbicide rate ($P=0.7743$). Similarly, in 2007, a high management system at quarter herbicide rate did not significantly reduce the amount of wild oat seedling survivors compared to a low management system at full herbicide rate ($P=0.6055$). But in 2007, there were significantly fewer wild oat seedling survivors in the high management system at quarter herbicide rate than low management system at half herbicide rate ($P<0.0001$).

At the half herbicide rate, crop rotation was the most influential agronomic practice reducing wild oat survivors ($P<0.0001$). All treatments under the Rot treatment had significantly fewer wild oat survivors than the Short-1X-Cont treatment. No significant difference in the number of wild oat seedling survivors was found between the Tall-2X-Rot treatment at half herbicide rate and the Short-1X-Cont treatment at full herbicide rate in 2006 and 2007.

Under the full herbicide rate, diverse crop rotation ($P<0.0001$) and tall barley cultivar ($P<0.0001$) were the optimum management strategies reducing wild oat seedling survivors in 2007. In 2006, no significant differences were found among rotation, barley cultivar or barley seeding rate at the full herbicide rate. All rotation treatments under full herbicide rates in 2006 and 2007 were significantly different from the Short-1X-Cont treatment. The number of survivors in 2006 and 2007 at the full herbicide rate under low management versus high management was reduced from 18 and 30 plants m^{-2} to 5 and 3 plants m^{-2}.

4.3.4. Management Implications

Emergence models were developed to improve the implementation of agronomic practices and chemical control measures. The timing of post-emergent herbicides is typically bound by crop staging or weed staging for maximum weed control and minimum crop tolerance issues. In this study, post-emergent herbicide applications in 2006 and 2007 occurred prior to 60% wild oat emergence. Although many farmers typically delay post-emergent graminicide applications to reduce wild oat escapes, the delay prolongs wild oat competition.

Early weed removal has been shown to consistently enhance crop yield through reductions of competitive early weeds (O'Donovan et al. 1985; Stougaard et al. 1997) or by reducing direct competition prior to weeds initiating shade avoidance in the crop (Liu et al. 2009). In general, late emerging weeds have been found to have little to no impact on crop yield (O'Donovan et al. 1985; Stougaard et al. 1997) but these studies did not address the seedling survivorship or fitness associated with delayed emergence. In general, herbicide-injured and late-emerging weeds have reduced fitness compared to early emerging and healthy weeds (Clay et al. 2005; Hartzler et al. 2004). Despite reports that late emerging weed seedlings are not a significant contributor to seed return (Bosnic and Swanton 1997; Swanton et al. 2008), results within this study indicate otherwise.

Between 40 and 50% of the wild oat continued to emerge following herbicide application and many of these weed seedlings set seed. The importance of late emerging wild oat seedlings is largely unknown, with the exception of some research from Europe demonstrating increased seedling mortality among later emerging *Avena* spp. (Chancellor & Peters 1972; Fernandez-Quitanilla et al. 1986). Under high management conditions, later emerging wild oat are relatively few and would be influenced by a competitive crop. Although low in numbers, they may be very important in the survival of wild oat populations in the seed bank. Under low management, late emerging wild oats are at high plant densities and would compete intra-specifically and inter-specifically. For example, under full herbicide rates and low management, 18-30 wild oat plants m^{-2} set seed. As such, this cohort is likely to contribute significantly to the cumulative increase in seed banks, wild oat biomass and seed production reported previously (Harker et al. 2009). In addition, later emerging wild oats are not being selected by herbicides, which may be a factor in delaying selection for herbicide resistance.

Adopting integrated weed management practices that are less reliant on herbicides can create opportunities to optimize crop health and delay or manage herbicide resistant weed populations. In this study, high management systems at low herbicide rates led to less wild oat emergence and seedling survivorship than low management systems at high herbicide rates. Combining optimal cultural practices, such as crop rotation, with low herbicide rates can reduce the rate of development of target- site weed resistance (Beckie and Kirkland 2003). Crop rotation significantly reduced wild oat emergence and seedling survivorship across herbicides; subsequently, incoporating competitive crops in a management system can enhance weed competition and facilitate herbicide rotation. Although herbicides are an effective weed control tool, diversifying cropping systems and practices can reduce herbicide use and therefore the selection of herbicide resistance.

Table 4.1. Field operations and dates at Lacombe, Alberta from 2006-2007.

Field Operations	**2006**	**2007**
Pre-seed herbicide application	May 05	May 08
Seeding (barley, canola)	May 04	May 11
Barley post-emergent herbicide application	May 31	June 05
Canola post-emergent herbicide application	June 01	n/a
Final seedling mortality counts	Aug. 10	Aug. 30
Barley harvest	Aug.16, 18*	Sept. 17
Canola harvest	**	n/a

* AC Lacombe barley harvested before Vivar harvested Oct. 15, 2006.

** No harvest as canola swaths were damaged by wind.

Table 4.2. Monthly mean air temperature and precipitation for Lacombe, Alberta, in the 2006 and 2007 growing season and the 30-year norm[a].

	Apr	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**
Temperature (°C)							
2006	6.7	11.3	15.3	17.6	14.7	11.1	2.4
2007	2.4	9.8	14.9	19.1	13.2	9.4	5.5
Thirty-year norm	4.3	10.1	13.9	15.4	14.7	9.8	4.5
Precipitation (mm)							
2006	7.5	55.1	66.4	89	74.4	50.6	38.6
2007	51.5	117.9	174	48.8	69.2	46	12.2
Thirty-year norm	21	55.6	75.7	89.4	70.8	47.3	16.6

[a] Thirty year norm is based on year between 1971 to 2000 from the Lacombe CDA2 weather station, Lacombe, Alberta.

Table 4.3. Parameter estimates (standard errors in parentheses) for emergence periodicity response of wild oat (T_{base}=0°C) in Lacombe, Alberta in 2006 and 2007. Cumulative percent emergence of wild oat was expressed as a function of accumulated growing degree days (GDD). A non-linear log-logistic model was fitted to the data (see Materials and Methods for a full description).

	Parameter estimates			Emergence		
Year	C[a]	D[b]	b[c]	E_{50}[d]	E_{90}[e]	R^2
				GDD[f]		
2006	0	100.9 (0.68)	-5.8 (0.14)	537 (2.44)	785 (9.31)	0.99
2007	0	101.3 (1.82)	-5.7 (0.42)	509 (6.37)	749 (28.62)	

[a] Lower limit (asymptote) of the response curve.
[b] Upper limit (asymptote) of the responsive curve.
[c] Slope.
[d] Growing degree days at 50% wild oat emergence.
[e] Growing degree days at 90% wild oat emergence.
[f] Growing degree days.

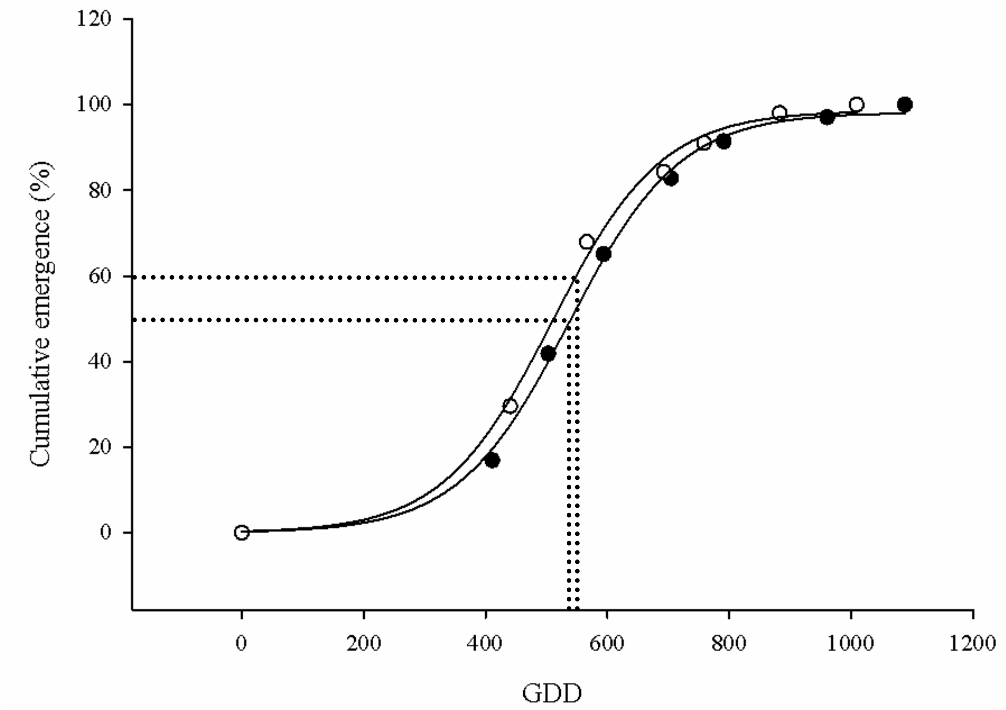
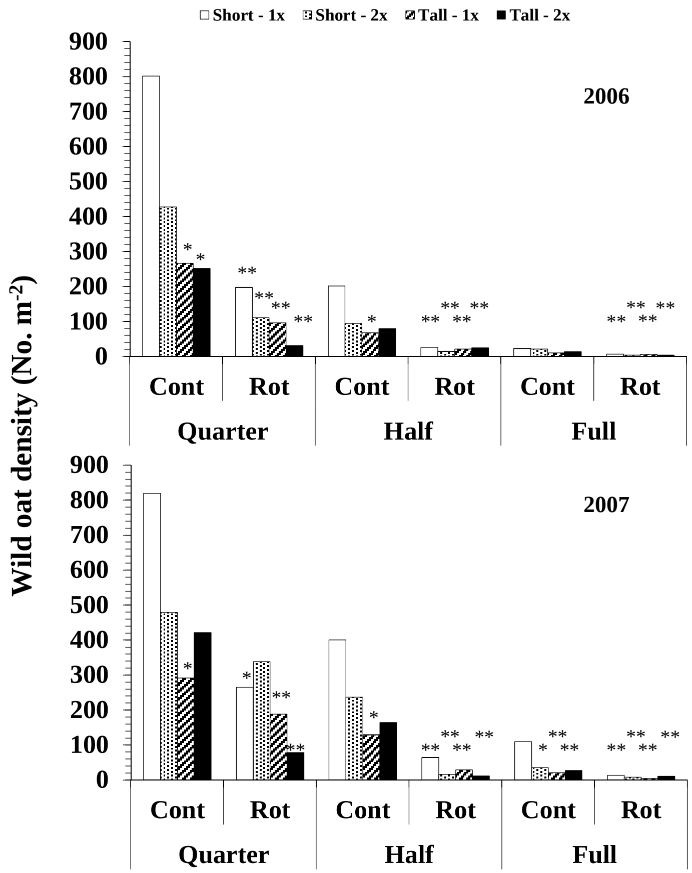


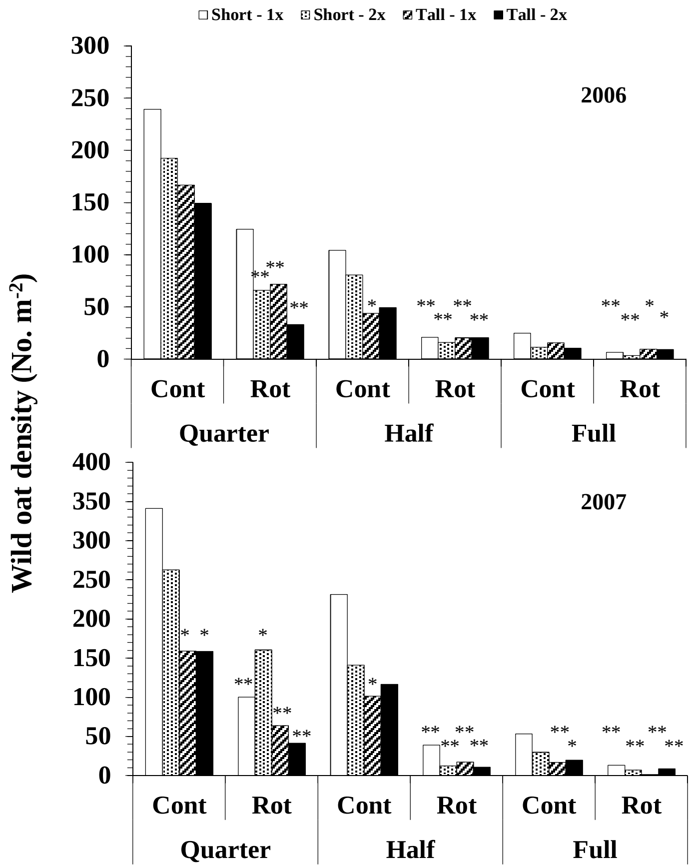
Figure 4.1. Cumulative wild oat emergence at Lacombe, Alberta in 2006 (●) and 2007 (○) as related to cumulative GDD T_{base} 0 °C. Lines represent a fitted log-logistic curve. (See Table 4.3. for parameter estimates). Dashed lines represents timing of post-emergent herbicides. In 2006, post-emergent herbicide were applied to barley and canola at 557 GDD and 573 GDD, respectively, corresponding to 53% and 55% cumulative wild oat emergence. Post-emergent herbicide application in barley during 2007 occurred at 566 GDD, corresponding to 57% cumulative wild oat emergence.



Contrast	*P* value
¼ - Short vs Tall	0.0003
¼ - 1x vs 2x Seed	0.0155
¼ - Cont. vs Rot.	<0.0001
½ - Short vs Tall	0.3481
½ - 1x vs 2x Seed	0.3042
½ - Cont. vs Rot.	<0.0001
Full - Short vs Tall	0.1891
Full - 1x vs 2x Seed	0.6408
Full - Cont. vs Rot.	<0.0001
¼-Rot-Tall-2x vs ½-Cont-Short-1x	0.0002
¼-Rot-Tall-2x vs Full-Cont-Short-1x	0.4889
½-Rot-Tall-2x vs Full-Cont-Short-1x	0.8304

Contrast	*P* value
¼ - Short vs Tall	0.0020
¼ - 1x vs 2x Seed	0.3885
¼ - Cont. vs Rot.	0.0002
½ - Short vs Tall	0.0070
½ - 1x vs 2x Seed	0.0081
½ - Cont. vs Rot.	<0.0001
Full - Short vs Tall	0.0056
Full - 1x vs 2x Seed	0.5493
Full - Cont. vs Rot.	<0.0001
¼-Rot-Tall-2x vs ½-Cont-Short-1x	0.0007
¼-Rot-Tall-2x vs Full-Cont-Short-1x	0.4668
½-Rot-Tall-2x vs Full-Cont-Short-1x	<0.0001

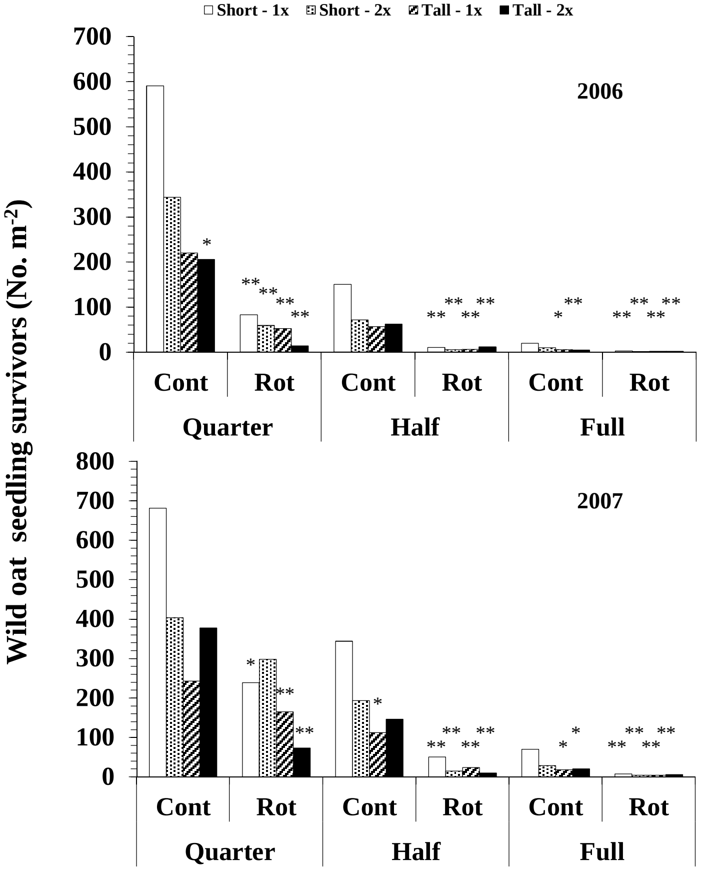
Figure 4.2. Mean wild oat plant density prior to post-emergent herbicide application in 2006 and 2007 at Lacombe, Alberta. Data are back-transformed means of log-transformed data. Pre-planned contrasts are listed beside each graph and are considered significant at P <0.004. The statistical significance of the difference between a given log-mean and the Short-1x-Cont treatment within each quarter, half and full herbicide rate are denoted '*' P < 0.05, '**' P < 0.01.



Contrast	*P* value
¼ - Short vs Tall	0.0312
¼ - 1x vs 2x Seed	0.0438
¼ - Cont. vs Rot.	<0.0001
½ - Short vs Tall	0.1968
½ - 1x vs 2x Seed	0.6388
½ - Cont. vs Rot.	<0.0001
Full - Short vs Tall	0.4014
Full - 1x vs 2x Seed	0.0445
Full - Cont. vs Rot.	0.0010
¼-Rot-Tall-2x vs ½-Cont-Short-1x	0.0087
¼-Rot-Tall-2x vs Full-Cont-Short-1x	0.5044
½-Rot-Tall-2x vs Full-Cont-Short-1x	0.6821

Contrast	*P* value
¼ - Short vs Tall	0.0001
¼ - 1x vs 2x Seed	0.7621
¼ - Cont. vs Rot.	<0.0001
½ - Short vs Tall	0.0114
½ - 1x vs 2x Seed	0.0115
½ - Cont. vs Rot.	<0.0001
Full - Short vs Tall	<0.0001
Full - 1x vs 2x Seed	0.4175
Full - Cont. vs Rot.	<0.0001
¼-Rot-Tall-2x vs ½-Cont-Short-1x	<0.0001
¼-Rot-Tall-2x vs Full-Cont-Short-1x	0.5019
½-Rot-Tall-2x vs Full-Cont-Short-1x	<0.0001

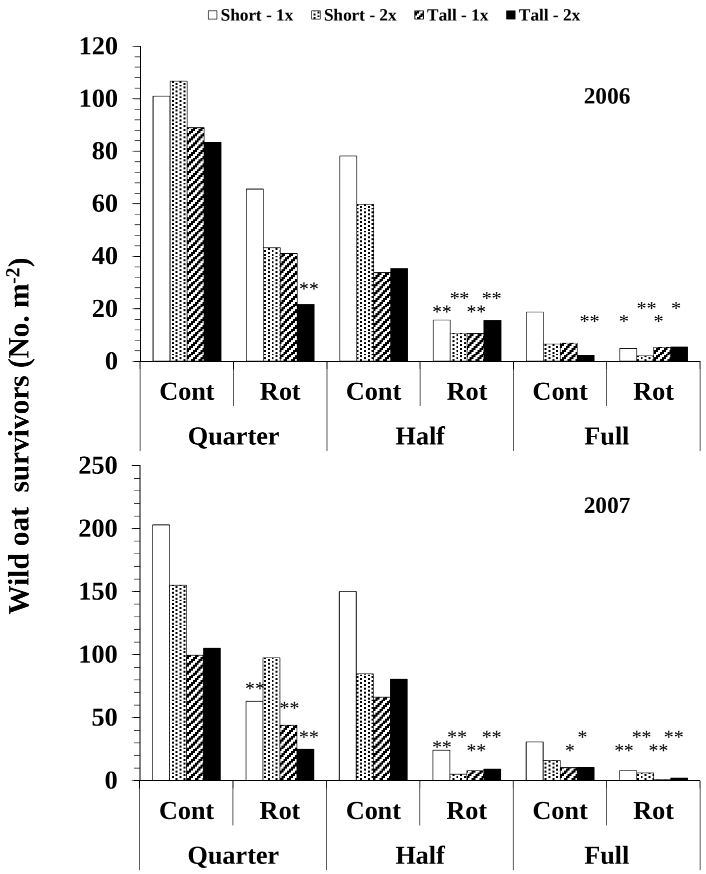
Figure 4.3. Mean wild oat plant density following post-emergent herbicide application in 2006 and 2007 at Lacombe, Alberta. Data are back-transformed means of log-transformed data. Pre-planned contrasts are listed beside each graph and are considered significant at P <0.004. The statistical significance of the difference between a given log-mean and the Short-1x-Cont treatment within each quarter, half and full herbicide rate are denoted '*' P < 0.05, '**' P < 0.01.



Contrast	*P* value
¼ - Short vs Tall	0.0014
¼ - 1x vs 2x Seed	0.0306
¼ - Cont. vs Rot.	<0.0001
½ - Short vs Tall	0.4111
½ - 1x vs 2x Seed	0.5586
½ - Cont. vs Rot.	<0.0001
Full - Short vs Tall	0.0931
Full - 1x vs 2x Seed	0.0993
Full - Cont. vs Rot.	<0.0001
¼-Rot-Tall-2x vs ½-Cont-Short-1x	<0.0001
¼-Rot-Tall-2x vs Full-Cont-Short-1x	0.5096
½-Rot-Tall-2x vs Full-Cont-Short-1x	0.3844

Contrast	*P* value
¼ - Short vs Tall	0.0074
¼ - 1x vs 2x Seed	0.5192
¼ - Cont. vs Rot.	0.0018
½ - Short vs Tall	0.0151
½ - 1x vs 2x Seed	0.0266
½ - Cont. vs Rot.	<0.0001
Full - Short vs Tall	0.0756
Full - 1x vs 2x Seed	0.4125
Full - Cont. vs Rot.	<0.0001
¼-Rot-Tall-2x vs ½-Cont-Short-1x	0.0040
¼-Rot-Tall-2x vs Full-Cont-Short-1x	0.9315
½-Rot-Tall-2x vs Full-Cont-Short-1x	0.0004

Figure 4.4. Mean wild oat seedling survivorship prior to post-emergent herbicide application in 2006 and 2007 at Lacombe, Alberta. Data are back-transformed means of log-transformed data. Pre-planned contrasts are listed beside each graph and are considered significant at P <0.004. The statistical significance of the difference between a given log-mean and the Short-1x-Cont treatment within each quarter, half and full herbicide rate are denoted ‘*’ P < 0.05, ‘**’ P < 0.01.



Contrast	*P* value
¼ - Short vs Tall	0.1303
¼ - 1x vs 2x Seed	0.2920
¼ - Cont. vs Rot.	0.0009
½ - Short vs Tall	0.1763
½ - 1x vs 2x Seed	0.8256
½ - Cont. vs Rot.	<0.0001
Full - Short vs Tall	0.3665
Full - 1x vs 2x Seed	0.0147
Full - Cont. vs Rot.	0.0951
¼-Rot-Tall-2x vs ½-Cont-Short-1x	0.0126
¼-Rot-Tall-2x vs Full-Cont-Short-1x	0.7743
½-Rot-Tall-2x vs Full-Cont-Short-1x	0.7368

Contrast	*P* value
¼ - Short vs Tall	0.0008
¼ - 1x vs 2x Seed	0.6772
¼ - Cont. vs Rot.	<0.0001
½ - Short vs Tall	0.0862
½ - 1x vs 2x Seed	0.0427
½ - Cont. vs Rot.	<0.0001
Full - Short vs Tall	<0.0001
Full - 1x vs 2x Seed	0.6780
Full - Cont. vs Rot.	<0.0001
¼-Rot-Tall-2x vs ½-Cont-Short-1x	<0.0001
¼-Rot-Tall-2x vs Full-Cont-Short-1x	0.6055
½-Rot-Tall-2x vs Full-Cont-Short-1x	0.0057

Figure 4.5. Mean wild oat seedling survivorship following post-emergent herbicide application in 2006 and 2007 at Lacombe, Alberta. Data are back-transformed means of log-transformed data. Pre-planned contrasts are listed beside each graph and are considered significant at P <0.004. The statistical significance of the difference between a given log-mean and the Short-1x-Cont treatment within each quarter, half and full herbicide rate are denoted '*' P < 0.05, '**' P < 0.01.

4.4. Literature Cited

Blackshaw, R. E. 2003. Soil temperature and soil water effects on pygmyflower (*Androsace septentrionalis*) emergence. Weed Sci. 51:592-595.

Adkins, S. W., M. Loewen, and S. J. Symons. 1986. Variation within pure lines of wild oats (*Avena fatua*) in relation to degree of primary dormancy. Weed Sci. 34:859-864.

Anderson, R. 2003. An ecological approach to strengthen weed management in the semiarid Great Plains. Adv. Agron. 80:33-62.

Armstrong, L. J. and S. W. Adkins. 1998. Variation in photoperiod response of different isogenic lines of wild oats (*Avena fatua*). Weed Sci. 46:39-47.

Benech-Arnold, R. L., R. A. Sanchez, F. Forcella, B. C. Kruk, and C. M. Ghersa. 2000. Environmental control of dormancy in weed seed banks in soil. Field Crops Res. 67:105-22.

Blackshaw, R. E., H. J. Beckie, L. J. Molnar, T. Entz, and J. R. Moyer. 2005. Combining agronomic practices and herbicides improves weed management in wheat-canola rotations within zero-tillage production systems. Weed Sci. 53:528-535.

Blackshaw, R. E., K. N. Harker, J. T. O'Donovan, H. J. Beckie, and E. G. Smith. 2008. Ongoing development of integrated weed management systems on the Canadian Prairies. Weed Sci. 56:146-150.

Bosnic, A. C. and C. J. Swanton. 1997. Influence of barnyardgrass (*Echinochloa crus-galli*) time of emergence and density on corn (*Zea mays*). Weed Sci. 45:276-282.

Bullied, W. J., A. M. Marginet, and R. C. Van Acker. 2003. Conventional- and conservation-tillage systems influence emergence periodicity of annual weed species in canola. Weed Sci. 51:886-897.

Chen, C. C., G. Jackson, K. Neill, D. Wichman, G. Johnson, and D. Johnson. 2005. Determining the feasibility of early seeding canola in the northern great plains. Agron. J. 97:1252-1262.

Clay S. A., J. Kleinjan, D. E. Clay, F. Forcella, and W. Batchelor. 2005. Growth and fecundity of several weed species in corn and soybean. Agron. J. 97:294-302.

Clayton, G. W., K. N. Harker, J. T. O'Donovan, R. E. Blackshaw, L. M. Dosdall, F. C. Stevenson, and T. Ferguson. 2004. Fall and spring seeding date effects on herbicide-tolerant canola (*Brassica napus* L.) cultivars. Can. J. Plant Sci. 84:419-430.

Fernandez-Quitanilla, C., L. Navarrete, J. L. G. Andujar, A. Fernandez, and M. J. Sanchez. 1986. Seedling recruitment and age-specific survivorship and reproduction in populations of *Avena sterilis* L. SSP. L*udoviciana* (Durieu) Nyman. J. Appl. Ecol. 23:pp. 945-955.

Forcella, F., R. L. Benech Arnold, R. Sanchez, and C. M. Ghersa. 2000. Modeling seedling emergence. Field Crops Res. 67:123-139.

Harker, K. N., G. W. Clayton, R. E. Blackshaw, J. T. O'Donovan, and F. C. Stevenson. 2003. Seeding rate, herbicide timing and competitive hybrids contribute to integrated weed management in canola (*Brassica napus*). Can. J. Plant Sci. 83:433-440.

Harker, K. N., T. K. Turkington, G. W. Clayton, J. T. O'Donovan, and R. B. Irvine. 2009. Integrating cropping systems with cultural techniques augments wild oat (*Avena fatua*) management in barley [electronic resource]. Weed Sci. 57:326-337.

Hartzler, R. G., B. A. Battles, and D. Nordby. 2004. Effect of common waterhemp (*Amaranthus rudis*) emergence date on growth and fecundity in soybean. Weed Sci. 52:242-245.

Hou, J. Q., E. J. Kendall, and G. M. Simpson. 1997. Water uptake and distribution in non-dormant and dormant wild oat (*Avena fatua* L.) caryopses. J. Exp. Bot. 48:683-692.

Kvalseth, T. O. 1985. Cautionary note about R^2. Am. Stat. 39:279–285.

Kirkland, K. J. and E. N. Johnson. 2000. Alternative seeding dates (fall and april) affect *Brassica napus* canola yield and quality. Can. J. Plant Sci. 80:713-719.

Leeson J. Y., A. G. Thomas, and J. T. O'Donovan. 2006. Economic impact of alien weeds on wheat, barley and canola production. Proc. Canadian Weed Sci. Soc. Nov. 27-29. Victoria, BC .

Liu, J. G., C. J. Swanton, P. H. Sikkema, and K. J. Mahoney. 2009. The importance of light quality in crop-weed competition [electronic resource]. Weed Res. 49:217-224.

Martinson, K., K. Spokas, D. Archer, J. Wiersma, B. Durgan, and F. Forcella. 2007. An emergence model for wild oat (*Avena fatua*). Weed Sci. 55:584-591.

Myers, S. P., M. E. Foley, and M. B. Nichols. 1997. Developmental differences between germinating after-ripened and dormant excised *Avena fatua* L. embryos. Annals of Botany 79:19-23.

O'Donovan, J. T., R. E. Blackshaw, K. N. Harker, and G. W. Clayton. 2006. Wheat seeding rate influences herbicide performance in wild oat (*Avena fatua* L.) [electronic resource]. Agron. J. 98:815-822.

O'Donovan, J. T., K. N. Harker, G. W. Clayton, and L. M. Hall. 2000. Wild oat (*Avena fatua*) interference in barley (*Hordeum vulgare*) is influenced by barley variety and seeding rate. Weed Technol. 14:624-629.

O'Donovan, J. T., J. C. Newman, K. N. Harker, R. E. Blackshaw, and D. W. McAndrew. 1999. Effect of barley plant density on wild oat interference, shoot biomass and seed yield under zero tillage. Can. J. Plant Sci. 79:655-662.

O'Donovan, J. T., T. K. Turkington, N. Z. Lupwayi, K. N. Harker, G. W. Clayton, and C. A. Grant. 2008. Effect of nitrogen rate and placement and seeding rate on barley productivity and wild oat fecundity in a zero tillage system. Crop Sci. 48:1569-1574.

Sawhney, R. and J. M. Naylor. 1980. Dormancy studies in seed of *Avena fatua*. 12. Influence of temperature on germination behavior of nondormant families. Can. J. Bot. 58:578-581.

Sawhney, R. and J. M. Naylor. 1982. Dormancy studies in seed of *Avena fatua*. 13. Influence of drought stress during seed development on duration of seed dormancy. Can. J. Bot. 60:1016-1020.

Seefeldt, S. S., J. E. Jensen, and E. P. Fuerst. 1995. Log-logistic analysis of herbicide dose-response relationships. Weed. Tech. 9:218-227.

Sharma, M. P., D. K. McBeath, and W. H. Vanden-Born. 1976. Studies on the biology of wild oats. I. Dormancy, germination and emergence. Can. J. Plant Sci. 611-618.

Swanton, C. J., R. H. Gulden, K. Chandler, and K. J. Mahoney. 2008. Integrated weed management: Knowledge-based weed management systems [electronic resource]. Weed Sci. 56:168-172.

Chapter 5. Conclusions

5.1. Summary of Results

Development of integrated weed management (IWM) strategies with herbicide applications has an important role in managing weed populations in an economically, ecologically and socially sustainable manner. Incorporating knowledge of weed biology and weed ecology with agronomic practices may have long term benefits in reducing weed emergence, weed densities, weed-crop competition, weed seed inputs and weed seed bank densities (Blackshaw et al. 2008; Buhler 2002; Murphy et al. 2006). Despite being one of the most well-researched weeds in western Canada, additional information on the biology and ecology of wild oat (*Avena fatua* L.) is still required to optimize management efforts. As new technologies and cropping practices are introduced into western Canada, the impact that they have on wild oat populations requires further evaluation. The research presented in this thesis has provided additional information regarding the ecology and agronomy of wild oat and will contribute to improvements and new developments in integrated weed management systems for wild oat.

Several agronomic practices have been integral in the reduction of weed populations and enhancement of grain yield; as a result, combining practices provides synergy to enhance the long term management benefits (Anderson 2003). Studying the wild oat seed bank provided an excellent indicator of the success of cumulative effects integrated weed management strategies have on wild oat populations (reviewed in Chapter 3). Results from this research indicate:

- The use of diverse crop rotation (Barley-Canola (*Brassica napus* L.)-Barley-Peas (*Pisum sativum* L.) vs Continuous Barley), competitive barley cultivars (Tall vs Short) and higher barley (*Hordeum vulgare* L.) seeding rates (2X vs 1X) in combination with herbicides provided an effective strategy to reduce the wild oat seed bank, especially under quarter herbicide rates (Figure 3.1. and Figure 3.2.).

- The cumulative effects of using high management strategies (diverse crop rotation, tall barley cultivar and double barley seeding rate) was reflected in the wild oat seed bank after six and seven years of treatments.
- The rank of each practice on its influence to reduce seed bank densities: herbicides > crop rotation > barley cultivar > barley seeding.
- In some cases, using high management strategies with lower herbicide rates resulted in smaller wild oat seed banks than low management strategies with full herbicide rates.

The implementation of IWM strategies in western Canada varies greatly by farm and agro-ecological region. Growers may find economic limitations to adopting a combination of cultural weed practices, with decreased profits associated with growing a diversity of crops and increased costs associated with using increased seeding rates and competitive crop cultivars, despite off-setting costs resulting from reduced herbicide rates. IWM systems that include wider crop diversity, such as a winter cereal or perennial forage, may confer additional reductions in wild oat populations and yield benefits compared to annual cropping systems. In addition, adopting integrated weed management systems that diversify cropping systems with competitive crops create an opportunity to diversify herbicide rotations as well as potentially reduce the use of herbicides, thereby reducing the selection of herbicide resistance.

Despite the majority of seeds removed from the seed bank through germination, additional losses can occur from predation, microbial decay, aging or exposure to abiotic stresses such as extremes in temperature or freeze/thaw cycles (Gallandt et al. 2004). Determining the role agronomic practices have on enhancing wild oat seed mortality was determined in spring and fall seed banks (reviewed in Chapter 3). Results from this research indicate:

- Combining optimal agronomic practices (diverse crop rotation, tall barley cultivar and double barley seeding rate) did not significantly change seed mortality compared to less optimal agronomic practices (continuous barley rotation, short barley cultivar and normal barley seeding rate) (Figure 3.3. and Figure 3.4.).
- The rate of seed mortality averaged across all treatments in spring and fall 2006 was 83 and 84%, respectively, and 56 and 76%, respectively, in the spring and fall 2007.
- The amount of seed lost between fall 2006 and spring 2007 seed bank ranged from 0 to 65%, with greater seed losses occuring under treatments with larger wild oat seed banks.

In western Canada the factors that influence the proportion of weed seeds lost from the seed bank and the factors that increase seed mortality are not well understood. The role of seed predation by vertebrates and invertebrates requires further research. There are no studies that have identified species or feeding preferences of seed predators or the cropping practices that may favour predation on the Canadian Prairies.

Knowledge of factors that affect seed banks and seedling emergence can improve the development and implementation of IWM practices (Grundy 2003). Using wild oat seed banks to predict wild oat emergence can provide necessary tools for growers to estimate the magnitude of a wild oat population. In this research:

- A strong relationship occurred between the fall 2006 wild oat seed bank and spring 2007 wild oat emergence (R^2=0.76; Figure 3.5.) as well as between the spring 2007 wild oat seed bank and spring 2007 wild oat emergence (R^2=0.78; Figure 3.6.).
- Biomass and emergence are the best predictors of subsequent wild oat seed banks (Table 3.4.)
- Wild oat emergence best predicted wild oat seed banks compared to seed production and biomass across Beaverlodge, Fort Vermilion and Lacombe, Alberta (Table 3.5.).

The geographic diversity in wild oat populations indicates that additional information on seed banks, seed production, emergence and biomass is required to fully evaluate these relationships. Further examination will be needed to examine how seed production, seed bank densities and biomass predict seedling recruitment or to improve how seedling recruitment is characterized.

A fundamental principle behind IWM is the precise timing and application of cultural, mechanical, chemical or biological control measures to ensure timely weed control measures that promote crop competition and yield (Norris et al. 2003). Consequently, developing weed emergence models can improve the implementation of these control measures. The emergence potential and timing was characterized for wild oat in Lacombe, Alberta within IWM systems using thermal time (GDD) with a base temperature of 0°C (reviewed in Chapter 4). This research found:

- The wild oat population in Lacombe reached 50% emergence at 537 and 509 GDD in 2006 and 2007, respectively (Table 4.3. and Figure 4.1.).
- Between 40 and 50% of wild oat seedlings emerged following herbicide application, contributing seed to the wild oat seed bank.

Unlike wild oat, volunteer crops such as volunteer wheat (De Corby et al. 2007) and volunteer canola (Lawson et al. 2006) are early emerging weed species that can be easily managed with pre- or post-seed herbicide applications. Incorporating information on soil moisture and soil temperature would help increase the accuracy in predicting wild oat emergence (Martinson et al. 2007). A comprehensive hydrothermal time (HTT) emergence model using a consistent base temperature for wild oat has not been developed in western Canada. Delineation of genotypic variance in wild oat populations would also be required to ensure the model can be generally applied. Developing a model practical for growers and agricultural professionals to predict wild oat emergence for weed management practices would be an integral component to accompany field scouting and integrated weed management practices.

Similar to the seed bank study, wild oat seedling emergence was evaluated over the growing season in Lacombe, Alberta to identify the impact optimal cultural practices have on early and late emerging wild oats and the implications those practices have on seedling survivorship (reviewed in Chapter 4).

- Ranking each practice on its influence to reduce seedling seedling emergence and survivorship: herbicides > crop rotation > barley cultivar > barley seeding rate; although, crop rotation was the most consistent agronomic practice to have a significant effect across all herbicide rates.
- Combining optimal agronomic practices (diverse crop rotation, tall barley cultivar and double barley seeding rate), especially under quarter herbicide rates, reduced the amount of wild oat seedling emergence and seedling survivorship, both prior to and after the post-emergent herbicide (Figure 4.2, Figure 4.3., Figure 4.4. and Figure 4.5.).

- Using high management strategies with lower herbicide rates frequently resulted in less seedling emergence and survivorship than low management strategies at full herbicide rates.
- Later emerging wild oats found within high management systems are low in densities, but may play an important role in maintaining wild oat populations through additions to the seed bank.
- Later emerging wild oats found within low management systems are high in densities and contribute to the cumulative increases in wild oat populations.

The premise that late emerging weeds are not a substantial source of seed returns needs to be further studied. Unselected cohorts are likely to be diluted and slow the selection for herbicide resistance. Further examination of the fecundity and viability differences between cohorts in a wild oat population will improve our understanding of the evolution and spread of herbicide resistance.

Demonstrations of the cumulative effects of IWM practices are critical to their adoption. A growing group of progressive growers in western Canada are combining various agronomic practices to improve yield potential and profitability, and are seeing the additional benefits of enhanced weed management. In spite of the complex biology behind wild oat, knowledge on the relationships between wild oat populations and weed management practices will be a function of collaboration between the research community, agronomists and local farmers.

5.2. Literature Cited

Anderson, R. 2003. An ecological approach to strengthen weed management in the semiarid Great Plains. Adv. Agron. 33-62.

Blackshaw, R. E., K. N. Harker, J. T. O'Donovan, H. J. Beckie, and E. G. Smith. 2008. Ongoing development of integrated weed management systems on the Canadian Prairies. Weed Sci. 56:146-150.

Buhler, D. D. 2002. Challenges and opportunities for integrated weed management. Weed Sci. 50:273-280.

De Corby, K. A., R. C. Van Acker, A. Brûlé-Babel, and L. F. Friesen. 2007. Emergence timing and recruitment of volunteer spring wheat [electronic resource]. Weed Sci. 55:60-69.

Gallandt, E. R., E. P. Fuerst, and A. C. Kennedy. 2004. Effect of tillage, fungicide seed treatment, and soil fumigation on seed bank dynamics of wild oat (*Avena fatua*). Weed Sci. 52:597-604.

Grundy, A. C. 2003. Predicting weed emergence: A review of approaches and future challenges. Weed Res. 43:1-11.

Lawson, A. N., L. F. Friesen, and R. C. Van Acker. 2006. Emergence timing of volunteer canola in spring wheat fields in Manitoba. Weed Sci. 54:873-882.

Martinson, K., K. Spokas, D. Archer, J. Wiersma, B. Durgan, and F. Forcella. 2007. An emergence model for wild oat (*Avena fatua*). Weed Sci. 55:584-591.

Murphy, S. D., D. R. Clements, S. Belaoussoff, P. G. Kevan, and C. J. Swanton. 2006. Promotion of weed species diversity and reduction of weed seedbanks with conservation tillage and crop rotation. Weed Sci. 54:69-77.

Norris, R. F., E. P. Caswell-Chen, and M. Kogan. 2003. Concepts in integrated pest management. Upper Saddle River, NJ: Prentice Hall.

Appendix 1.

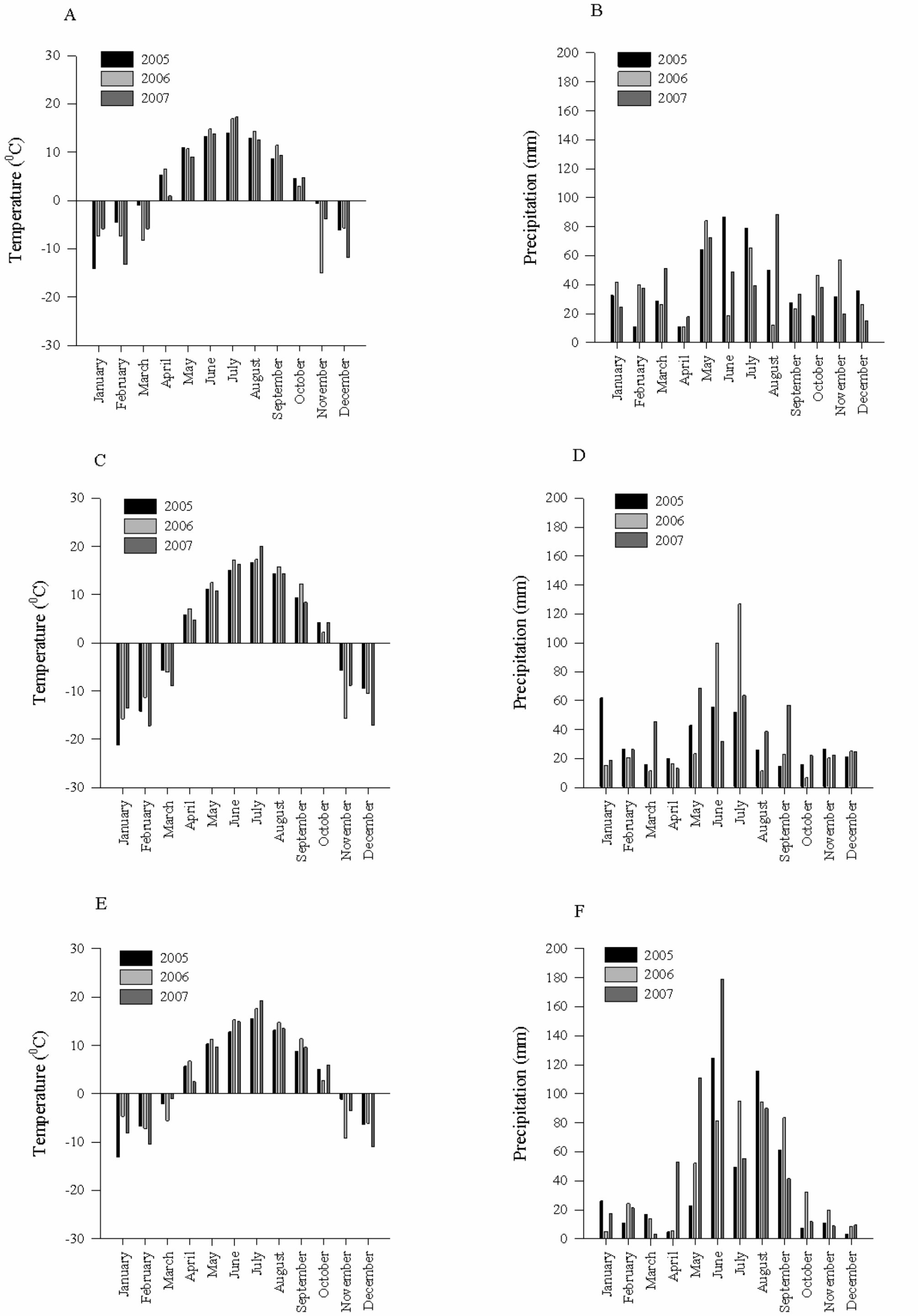


Figure A.1.1. Mean monthly air temperature (A, C, E) and precipitation (B, D, F) from 2005 to 2007 at Beaverlodge, Fort Vermilion and Lacombe, Alberta, respectively.