The Potential for Targeting Alternate Life Cycle Stages of Western Canadian Weeds

by

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Abstract

Over-reliance on herbicides to manage weeds in agricultural crops has selected for herbicide resistant weeds globally. Harvest weed seed control (HWSC), an Australian developed and optimized paradigm of weed control, targets newly shed seed to reduce seed bank inputs. For species to be managed by HWSC they must retain seeds until crop harvest at a canopy height where they will be collected by the harvester. Seed retention characteristics of wild oat, cleavers and volunteer canola were determined over six site-years in Alberta and Saskatchewan to determine their suitability for HWSC. Overall ranking of HWSC management potential was canola > cleavers > wild oat, with wild oat a concern due to economic impact and resistance levels.

A periodic demographic matrix model was developed to determine the potential impact of HWSC on population growth rates of wild oat and to identify other life cycle stages as potential control opportunities. The model emphasized that early seed shatter of wild oat limits potential of HWSC technologies on population management. Across tested treatments, 80% wild oat seed control was required before seed bank additions occurred for HWSC to reduce or stabilize populations. Potential life cycle stages for management included the over-winter seed bank, plant fecundity (seed production), and the growing season seed bank. The seed bank was a critical component of the wild oat life cycle, particularly when survival of newly shed seeds was limited.

Stationary threshing was used to evaluate the Harrington Seed Destructor (HSD), a HWSC technology, for the effects of weed species, weed seed size, seed number, chaff type and chaff volume on weed seed devitalization. This study determined that the HSD has > 97% efficacy on five problematic Canadian weed species, and that seed size was not likely to limit

management with > 98% control at all canola seed sizes tested. Increases in weed seed number or chaff volume significantly affected weed seed devitalization but the small differences were unlikely to be biologically relevant in the field. Volunteer canola devitalization was significantly decreased in canola chaff when compared to barley or pea chaff. This could be due to protective structures such as pods in the chaff or due to an underlying presence of volunteer canola in the chaff. Over all tested conditions and species, devitalization of seeds with the HSD was high, indicating that population control will be primarily limited by the ability to get seeds into the HSD and not HSD efficacy.

Germination stimulant compounds could provide an additional tool to manage seeds shed prior to harvest, or that are produced below harvest cutting height. Compounds would either induce germination prior to environment-induced mortality, or have herbicidal effects. Fluridone, which has been previously reported to have both germination stimulant and herbicidal effects, was tested in western Canada for stimulant properties in field studies with fall applications, as well as rotational crop tolerance. No significant stimulation was observed, however there were indications of potential stimulant activity. Rotational crop tolerance of canola was poor, including severe injury and death. In this study the risks of fall fluridone applications outweighed the potential benefits of weed germination stimulation.

Overall, the potential of HWSC in western Canada was highlighted with limitations for Canadian producers also identified. Wild oats have poor potential to be managed by HWSC, and the seed bank and fecundity were identified as future management targets. Additionally, fluridone applications to manage seeds not available for HWSC led to rotational crop damage and limited germination stimulant efficacy. None of the tested methods provided a complete solution to herbicide resistant or susceptible weeds but may be useful additions to integrated weed management systems in western Canadian crops.

Preface

Chapter 3 was co-authored by the candidate, Dr. Linda Hall, Dr. Neil Harker, Dr. Hugh Beckie, Mr. Eric Johnson, and Dr. Craig Stevenson. The candidate was responsible for trial design with input and guidance from Dr. Hall, Dr. Harker and Dr. Beckie. The candidate was also responsible for major data collection, statistical analysis and manuscript preparation. Mr. Eric Johnson, Dr. Linda Hall and Dr. Neil Harker hosted trial locations and their technical staff provided support. Dr. Craig Stevenson provided statistical analysis support, guidance and recommendations. All co-authors provided manuscript writing support and editing. A version of chapter 3 has been accepted for publication in *Weed Science*: Tidemann BD, Hall LM, Harker KN, Beckie HJ, Johnson EN, Stevenson FC. 2017. Suitability of Wild Oat (*Avena fatua*), False Cleavers (*Galium spurium*) and Volunteer Canola (*Brassica napus*) for Harvest Weed Seed Control in Western Canada. Weed Science (Accepted – in press).

Chapter 4 was co-authored by the candidate, Dr. Linda Hall, Dr. Neil Harker, and Mr. Brendan Alexander. The candidate was responsible for parameterization and running of the model, as well as perturbation analyses. Dr. Hall and Dr. Harker provided guidance and advice. Dr. Harker also provided data from previous studies. Mr. Alexander provided demographic model guidance and conducted the bootstrapping in R. The candidate was responsible for manuscript preparation with editing and input from all other co-authors. This chapter was published in *Weed Science*: Tidemann BD, Hall LM, Harker KN, Alexander BCS. 2016. Identifying Critical Control Points in the Wild Oat (*Avena fatua*) Life Cycle, and the Potential Effects of Harvest Weed Seed Control. Weed Science 64(3): 463-473.

Chapter 5 was co-authored by the candidate, Dr. Linda Hall, Dr. Neil Harker, and Dr. Hugh Beckie. The candidate was responsible for trial design with input and suggestions from the other co-authors. The candidate was responsible for conducting the trial, sample cleaning and collection and germinations, with help from the technical staff of Dr. Harker. The candidate was responsible for statistical analysis and manuscript preparation, with editing, input and suggestions from the other co-authors. This chapter has been accepted for publication in *Weed Science*: Tidemann BD, Hall LM, Harker KN, Beckie HJ (2017) Factors affecting weed seed devitalization with the Harrington Seed Destructor. Weed Science 65: 650-658.

Chapter 6 was co-authored by the candidate, Dr. Linda Hall, Dr. Neil Harker, and Dr. Hugh Beckie. The candidate was responsible for trial design with input from the co-authors. Dr. Linda Hall and Dr. Neil Harker hosted trial locations and their technical staff assisted with conducting the trials. The candidate was responsible for trial spraying, data collection in Lacombe, data collation across locations, statistical analysis and manuscript preparation. The co-authors provided suggestions and advice on the statistical analysis as well as editing and contributing to the writing of the manuscript. A version of this chapter has been accepted for publication in *Weed Technology*: Tidemann BD, Hall LM, Harker KN, Beckie HJ (2017) Potential Benefit and Risk of Fluridone as a Fall Germination Stimulant in Western Canada (Accepted – In Press).

Dr. Linda Hall and Dr. Neil Harker who were co-authors on each chapter were also co-supervisors of the candidate's Ph.D. program. Dr. Hugh Beckie was a member of the supervisory committee.

Dedication

This thesis is dedicated to my Grandma Morrison who isn't here to see me finish it but whose whistles and cheers I can hear from here. Te quiero.

And to my husband, Torstein, who felt that having my M.Sc. thesis dedicated to him was not as good as having a Ph.D. thesis dedicated to him. Now you have both.

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List of Abbreviations

ACCase	Acetyl co-enzyme A carboxylase
ai	active ingredient
ALS	Acetolactate synthase
ANOVA	analysis of variance
C	Celsius
CAD	Canadian dollars
cm	centimetre
d	days
DAT	days after treatment
g	grams
GDD	growing degree days
ha	hectare
HRAC	Herbicide Resistance Action Committee
HSD	Harrington Seed Destructor
HWSC	Harvest Weed Seed Control
iHSD	integrated Harrington Seed Destructor
IWM	integrated weed management
kg	kilogram
L	litre
LTA	long term average
LTRE	life table response experiment
m	metre
mL	millilitre

mm	millimetre
PDS	Phytoene desaturase-inhibiting
RIM	ryegrass integrated management model
RPM	revolutions per minute
s	seconds
sds.	seeds
Spp.	species
TSW	thousand seed weight
wk	week
WSSA	Weed Science Society of America

Chapter One: Introduction

1.1. Background

Weeds compete with crops for light, nutrients and resources, which results in average yield losses of up to 34% globally (Oerke 2006), but can result in more severe losses depending on weed species, weed density and crop. In addition, weeds can provide habitat and more suitable environments for insects and disease-causing pathogens which can also be detrimental to the crops (Buhler 2002; Norris and Kogan 2000). In response, most weeds in global agriculture are managed with herbicide applications (Buhler et al. 2000; Vencill et al. 2012), most of which are applied to manage the seedling stage of the weeds. As a result of herbicide over-reliance, herbicide resistance has evolved in 483 weed species (Heap 2017) world-wide.

Herbicide resistance is continuously increasing globally and in western Canada (Beckie et al. 2013; Heap 2017). As resistance evolves the primary solution looked for by producers is a new herbicide or new herbicide mode of action (Beckie 2006). This however, simply shifts the selection pressure for resistance to new molecules or herbicide groups; it does not stop selection. There have been no new herbicide modes of action for nearly three decades (Duke 2012), and there are none likely to be introduced in the near future (Owen 2016). This has resulted in a need for new and additional management practices in agricultural crops to manage weeds, particularly those that target additional life cycle stages that could be used in combination with herbicides.

Harvest weed seed control (HWSC) has been investigated and optimized in Australia in response to herbicide resistant weeds. HWSC is a paradigm of control methods that target seed bank inputs of mature weeds at crop harvest (Walsh et al. 2013). There are a number of potential control techniques within this paradigm including narrow windrow burning, direct baling, chaff cart collection combined with burning or grazing, narrow windrow rotting, chaff decks and physical impact implements (Australian Herbicide Resistance Initiative 2014; Australian Herbicide Resistance Initiative 2016; Seed Terminator 2017; Walsh et al. 2013). Physical impact implements include the Harrington Seed Destructor, the integrated Harrington Seed Destructor, and the Seed Terminator (de Bruin Engineering 2017; Seed Terminator 2017; Walsh et al. 2012). Some HWSC methods have been shown to be equivalent in terms of weed management (Walsh et al. 2017), and it is believed they are all highly effective. Regardless of which method is chosen there are two requirements for weeds to be compatible with this approach: 1) weed seeds must be retained on the plant at the time of crop harvest (Walsh et al. 2014), and 2) the weed seeds must be produced and retained at a height from which they can be collected (Walsh et al. 2016). These criteria are met by some major Australian weeds, but the suitability of weeds in other agricultural regions has not been well studied. Determining if these techniques will be effective on their weed species is critical to adoption by western Canadian producers. While these techniques do not manage the weed seeds already in the seed bank, which has been identified as a potentially important target by demographic modelling (Davis 2006), they do target seed bank inputs rather than the seedling stage.

The physical impact implements have been identified as the most likely harvest weed seed control technologies to be adopted on a wide scale in western Canada due to burning, farming system, climate and marketing restrictions with the other techniques. Of the physical control implements, the Harrington Seed Destructor has been most extensively tested; however these experiments have been primarily located in Australia. It is known that seed and crop parameters such as seed size, external seed components, chaff type and chaff volume are likely to affect efficacy with physical implements such as the Harrington Seed Destructor (Berry et al. 2015). In order for harvest weed seed control technologies to be adopted in western Canada, it must be shown that efficacy on weeds being targeted by these technologies is high, and that cropping system parameters such as different chaff types will not decrease their efficacy.

The seed bank has been identified as an important target for weed management techniques, particularly for annual plants (Davis 2006) as it provides a temporal reserve for the population. Additionally, larger seed banks are generally correlated with higher risk of resistance due to higher likelihood of a resistant mutant being present (Bagavathiannan and Norsworthy 2012), so management of the seed bank may be critical to prevention and management of herbicide resistant weed populations. Encouraging fatal germination or microbial decay are two potential mechanisms by which to target the weed seed bank (Fenner and Thompson 2005; Kremer 1993). Fatal germinations could be encouraged by the application of chemicals which stimulate plant emergence in a climate not suitable for growth. Ammonium nitrate, ethylene and compounds in smoke have been shown to stimulate germination of some weeds (Egley 1986; Fenner and Thompson 2005; Papenfus et al. 2015; Sexsmith and Pittman 1963; Stevens et al. 2007). Additionally, fluridone, an aquatic and agricultural herbicide compound, has been shown recently to also have germination stimulant activity (Goggin and Powles 2014). It could potentially be used to cause fatal germination of weeds in the fall which would then be killed by winter freezing or fluridone's herbicidal activity. The herbicidal activity would aid in managing facultative winter annuals such as false cleavers (*Galium spurium* L.). However, fluridone has only been tested under Australian conditions for germination stimulant activity to date (Goggin and Powles 2014), and safe re-cropping intervals have not been established for Canadian crops.

Demographic modelling has been used in ecology to determine the status of an organism's population. It has been demonstrated that demographic models can also be used in weed science to compare effectiveness of treatments (Davis et al. 2003). These models can also be used to aid in decision making regarding implementation of new technologies such as harvest weed seed control. It is understood that higher seed retention makes a weed species a better target for harvest weed seed control methods; however, we do not understand what percentage of seeds must be collected to see management effects on the population. Demographic modelling can be used to determine what percentage of seeds must be destroyed to cause a population decline for that species. The value will be species dependent and affected by seed dormancy, fecundity, and survival as a plant and in the seed bank.

As herbicide resistance in western Canada continues to increase, the concurrent need for new management technologies does too. Harvest weed seed control may provide a new weed management method for western Canada, and modelling can aid in determining whether the addition of HWSC to weed management systems is effective. However, tools such as the Harrington Seed Destructor have not been tested on Canadian weeds and crops, a necessity for widespread Canadian adoption. For weeds not well suited for HWSC methods, additional management methods such as putative germination stimulants should be evaluated for their efficacy. Therefore, the following research objectives were set for this thesis.

1.2. Research Objectives

1.2.1. Determine the suitability of driver weed species for harvest weed seed control by determining seed retention and height of seed retention.

If harvest weed seed control is to be used in western Canada, driver weed species must have high seed retention at crop harvest and must retain their seeds at a collectable height. Three driver weeds in western Canada are wild oat (*Avena fatua* L.), false cleavers and volunteer canola (*Brassica napus* L.). Their seed retention and height of seed production has been measured on a limited geographic scale in western Canada (Burton et al. 2016; Burton et al. 2017; Shirtliffe et al. 2000). Additionally, the height of seed retention aspect of these weeds has not been well studied. This research objective was investigated in Chapter 3 with the following hypotheses.

- Seed retention over time will vary by species as well as by trial location.
- Height of seed retention will vary by species.
- Seed retention over time and height of seed retention will be affected by crop competition.

1.2.2. Determine potential target life cycle stages of wild oat and the potential effects of harvest weed seed control on wild oat population growth rate.

Wild oat is the most economically important weed in western Canada and is also the predominant herbicide resistant weed problem in the region (Beckie et al. 2012). Demographic models allow an *a priori* evaluation of the effects of new management strategies such as harvest weed seed control to determine if they would be beneficial additions to a management system (Davis et al. 2006). Additionally, demographic models can identify life cycle stages which would potentially make good management targets (Davis 2006). As previous studies indicated low wild oat seed retention at harvest timing (Burton et al. 2016; Burton et al. 2017; Shirtliffe et al. 2000), demographic modelling could be used to determine the required efficacy level of HWSC to impact the wild oat population growth rate. This research objective was investigated in Chapter 4 with the following hypotheses.

- As an annual weed with moderate seed bank persistence, survival in the seed bank is likely important for wild oat population growth rate.
- As preliminary results from Objective 1.2.1 suggested limited seed retention of wild oat at harvest, harvest weed seed control will have a limited impact on wild oat population growth rate.
- Life cycle stages with significant impact on overall wild oat population growth rate will be identified as new target stages for management.

1.2.3. Determine the effects of weed species, weed seed size, weed seed number, chaff volume and chaff type on the efficacy of the Harrington Seed Destructor.

If HWSC becomes an adopted practice in western Canada, the most likely method to be used by producers is use of the physical impact implements. Particularly with the release of the integrated units, this method minimizes time and labour inefficiencies as well as detrimental environmental effects (Australian Herbicide Resistance Initiative 2014; Australian Herbicide Resistance Initiative 2016). There are known variables that affect devitalization capabilities of physical impact implements (Berry et al. 2015). However, these implements have not been tested on western Canadian weeds, and the operating conditions in western Canada have not been well defined. As the Seed Terminator was unavailable until 2017, stationary testing was conducted using the HSD in Chapter 5 with the following hypotheses.

- Weed species will not all be equally controlled by the Harrington Seed Destructor.
- Weed seed size will significantly impact control with the Harrington Seed Destructor; larger seeds will be devitalized more effectively.
- Weed seed number will significantly impact control with the Harrington Seed Destructor; as the number of seeds increase, control will decrease.

- Chaff volume will significantly impact control with the Harrington Seed Destructor; as the amount of chaff increases, the proportion of seeds devitalized will decrease.
- Chaff type will not significantly affect devitalization of weed seeds by the Harrington Seed Destructor.

1.2.4. Determine the potential for fluridone to be use as a germination stimulant in western Canada.

If new weed technologies such as HWSC are not effective at preventing seed bank inputs, or for weeds that subsist for longer periods of time in the seed bank, management methods which target seed bank survival will be needed. A germination stimulant could be highly valuable in western Canada where additional control measures after weed emergence may not be required if emergence is timed just prior to high mortality winter months. However, with problematic winter annual weeds such as cleavers, a germination stimulant with herbicidal effects is desirable. Fluridone has the potential to meet these characteristics (Goggin and Powles 2014). This research objective is investigated in Chapter 6 with the following hypotheses.

- Fall fluridone application will increase the emergence of weeds in the fall, relative to areas without fluridone application.
- Fall fluridone application will result in reduced weed populations in the spring, relative to areas without fluridone application.
- Fall fluridone applications will not affect the growth of subsequent crop populations.
- Fall fluridone applications will be differentially effective on broadleaf and grass weeds.

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Chapter Two: Literature Review

2.1. Weeds as Crop Pests

Weeds have been, and will continue to be agricultural crop pests due to the dynamic and responsive nature of their populations (Buhler 2002). Weeds compete with crops for light, nutrients and resources, which results in average yield losses of up to 34% globally (Oerke 2006), but can result in more severe losses depending on weed species, weed density and crop. Weeds can also cause crop quality losses (Oerke 2006). Within a cropping system, weeds may also act as a food source for insect pests, change habitat dynamics that alter insect population levels, or act as food or habitat for beneficial insects (Buhler 2002; Norris and Kogan 2000). Insects may also cause injury to the crop plants through feeding, providing a less competitive crop environment where the weed can grow more successfully (Norris and Kogan 2000). Weeds also interact with pathogens by serving as bridge organisms or alternate hosts (Buhler 2002). Management of weeds is undertaken to preserve crop yield and quality, prevent crop competition and minimize seed contamination. However, management methods employed for weeds may also affect insect and disease populations which also consequently affect crop quality and competition (Buhler 2002; Norris and Kogan 2000). Weed management is only one of many necessary cropping system practices.

Herbicide application targets weeds prior to emergence or as seedlings, and is an easy, economical and effective tool in many cropping systems (Buhler et al. 2000). It is also the dominant weed management practice in most global cropping systems (Buhler et al. 2000; Vencill et al. 2012). However, over-reliance on herbicides has resulted in consumer concerns about the environment and public health (Buhler et al. 2000; Liebman and Gallandt 1997), as well as weed resistance to herbicides (Heap 2017). These effects have increased interest in new methods of managing weeds (see below).

2.2. Herbicide Resistance

Herbicide resistance is defined as "the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to the wild type" by the Weed Science Society of America (1998).

2.2.1. Selection and incidence of herbicide resistance

Herbicide application does not cause herbicide resistance; herbicide application selects for those plants with naturally occurring herbicide resistance traits (Vencill et al. 2012). Herbicide resistance traits occur through natural or induced mutations (Weed Science Society of America, 1998) and are those traits that inhibit or minimize herbicidal effects to the extent that they are no longer lethal. When herbicides are applied to a large, genetically diverse weed population within a field, they select for those individuals with mutations conferring resistance. This exerts a selection pressure for resistance. Selection pressure is affected by genetic, herbicide, operational and weed species' biology characteristics (Powles and Yu 2010). Genetic variables include the frequency, number, dominance and fitness cost of resistance genes (Jasieniuk et al. 1996; Powles and Yu 2010). Populations with higher frequency and higher number of genetic mutations are more easily selected for resistant individuals, and dominant resistance genes are more easily established within a population. Herbicide characteristics such as chemical structure, site of action and residual activity affect rate of evolution through the number of individuals the selection pressure acts on (Powles and Yu 2010). Additionally, the number of mutations affecting the herbicide target site without detrimentally affecting the plant's growth and reproduction affect selection and rate of selection for resistance (Powles and Yu 2010). Operational aspects such as herbicide dose, operator skill and accuracy, and agro-ecosystem factors also influence the selection pressure for resistance (Powles and Yu 2010). Weed biology also influences the ability of a resistance mutation to be selected for and establish within a population; weeds which are allogamous, produce many seeds and have high capacity for gene flow are more likely to be selected for resistance (Jasieniuk et al. 1996; Powles and Yu 2010). Fitness penalties associated with resistance mutations and gene flow of the mutations have been identified as key parameters in understanding the dynamics of herbicide resistance (Maxwell et al. 1990). Population densities have also been associated with the risk of herbicide resistance developing; more individuals in a weed population, whether above ground or in the seed bank, increases the likelihood that resistance will evolve within that population (Bagavathiannan and Norsworthy 2012; Jasieniuk et al. 1996). Some of the factors that affect selection pressure can also impact the mechanism of resistance in a weed population.

Resistance mechanisms are usually either target site or non-target site based (Prather et al 2000; Vencill et al. 2012). Target site mechanisms are those that affect the target site directly and include target site genetic mutations that affect herbicide activity, and gene amplification (Powles and Yu 2010; Gaines et al. 2010; Gaines et al. 2011). Non-target site resistance mechanisms include increased herbicide metabolism, changes in herbicide translocation, sequestration of the herbicide molecule, and altered herbicide uptake (Powles and Yu, 2010). Rapid necrosis of treated leaves preventing translocation to the meristems of the plants has also been observed (Sammons and Gaines 2014). Typically, a mechanism of action is described for resistance to a single herbicide group. However, cross-resistance (resistance to more than one herbicide or group due to one mechanism) and multiple resistance (resistance to more than one herbicide group due to two or more mechanisms) occur (Heap 2014; Prather et al. 2000). The latter types of resistance are of greater concern due to their ability to quickly limit herbicide control options. These are becoming more common in North America; a kochia (*Kochia scoparia* L. Schrad) population is resistant to 4 herbicide modes of action (Heap 2017) and a wild oat (*Avena fatua* L.) population is resistant to 5 herbicide modes of action (Heap 2017, Mangin 2016).

Herbicide resistance is a global issue with 483 unique cases (species x site of action) and over 250 species exhibiting herbicide resistance (Heap 2017). The United States has the highest incidence of resistance (158 unique cases), followed by Australia (84) and Canada (65) (Heap 2017). Resistance to acetolactate synthase (ALS) inhibiting herbicides is most widespread in Canada (Heap 2017), however acetyl co-enzyme A carboxylase (ACCase) resistance has also become a widespread and costly issue in grass weeds. Glyphosate resistance has become a significant problem in some areas of the world (Heap 2017), likely related to increased selection pressure from high levels of adoption of glyphosate resistant crops (Powles 2008). In Canada there are currently 5 unique cases of glyphosate resistance with only 1 species resistant to glyphosate in western Canada (Heap 2017), in addition to herbicide-resistant canola crop volunteers. However, these numbers are expected to increase in the near future, with specific species identified as high risk in certain agro-ecoregions based on weed abundance and glyphosate use patterns (Beckie et al. 2013b).

2.2.2. Management of herbicide resistance

In most cases the first response to identified herbicide resistance is to alter herbicide management by changing chemicals, changing herbicide groups, or increasing the overall number of herbicides or herbicide groups used (Beckie 2006). Both herbicide tank mixes and herbicide rotation can be useful for the management of herbicide resistant weeds (Beckie 2006; Norsworthy et al. 2012; Owen 2016), however, tank mixes are typically more effective at delaying evolution of future resistant biotypes (Beckie and Reboud 2009). Use of alternative or additional herbicides to manage herbicide resistance changes the scope of resistance selection but does not cease selection. This can result in the evolution of multiple-resistance leading to significantly limited herbicide options (Heap 2014). However, integrated herbicide management alone is not enough to mitigate resistance in the long term (Harker et al. 2012). Increased use of novel or less commonly used herbicides increases their selection intensity for resistance. However, no new major herbicide modes of action have been introduced for nearly three decades, and none are being developed that are near commercialization (Duke 2012; Owen 2016). Fewer agricultural chemical companies, reduced investment in novel chemical discovery, and increased costs to discover and register a new herbicide contribute to this lack of new herbicide modes of action, in addition to the likelihood that the easy to find modes of action have already been discovered. Continued reliance solely on herbicides for herbicide resistance management is not a sustainable practice (Owen 2016).

Best management practices for herbicide resistant weeds have long promoted other management methods in addition to herbicide use (Beckie 2006; Beckie and Harker 2017; Norsworthy et al. 2012; Owen 2016). Management of weeds through the use of cultural, biological and physical tactics in addition to herbicides, with strategies selected based on weed biology, is known as integrated weed management (IWM), a form of integrated pest management (Buhler 2002; Harker and O'Donovan 2013). This is also often referred to as the “many little hammers” approach or ecological weed management (Liebman and Gallandt1997). Herbicide resistance management recommendations often include combinations of these different types of tactics including crop rotation, increased seeding rate, weed seed capture or prevention, use of mulches or cover crops, and tillage, among other tactics (Beckie 2006; Beckie and Harker 2017; Buhler 2002 Liebman and Gallandt 1997; Prather et al. 2000; Norsworthy et al. 2012). While many tactics have been identified and diversity in control is often recommended, acceptance of the diverse management approach and implementation of these tactics by producers has been limited (Beckie 2006, Owen 2016). Economics, or perceived economic impact, as well as the relatively lower efficacy and increased labour requirements of non-herbicide management strategies when compared to the relatively simplistic and cheap herbicide options available often limit adoption of additional practices (Beckie 2006, Owen 2016). Furthermore, producers tend to devise strategies to manage resistance only once the problem becomes ‘real’ on their farm (Owen 2016); prevention is not the focus of current weed management strategies. While in some cases there is a measured economic benefit to preventing herbicide resistance (Gerhards et al. 2016), producers do not perceive the existence of this benefit when formulating their weed management strategies (Owen 2016).

Mathematical and theoretical models can be used as decision aid mechanisms by producers when developing their weed management system (Davis 2006). Specific models such as the ryegrass integrated management (RIM) model have been developed to aid decision making by producers regarding which management tactics to include in their production system to delay and manage herbicide resistance (Lacoste and Powles 2014; Pannell et al. 2004). Models can also be used to make decisions on new weed management technologies to determine if they can be effectively implemented (Davis et al. 2006). Demographic matrix models have been used to aid in implementation and testing of new weed management tactics (Davis and

Liebman 2003; Davis et al. 2006). While the general form of such models can be applicable to multiple species, they must be parameterized for each species specifically.

2.3. Matrix Modelling of Population Growth Rates

Demographic modelling through the use of matrix models is commonly used in ecology and conservation biology, although it is less common in agriculture and weed management (Davis et al. 2004). Matrix models of populations use life cycle demographic parameters (i.e. fecundity, survival, etc.) to determine population growth rates of species (de Kroon et al. 2000). Demographic parameters are also often referred to as vital rates (Caswell 2000). The life cycle is described using a life cycle diagram, a visual depiction of the vital rates that illustrates the structure of the population projection matrix $\boldsymbol{A}$ (Caswell 2001). The $\boldsymbol{A}$ matrix describes the changes in a population vector n_t when compared with the same population vector after a time step (n_{t+1}) (Caswell 2001); in most studies the time step is equal to a year. This relationship means that n_{t+1} is equivalent to the product of $\boldsymbol{A}$ and n at the initial evaluation time (t) (Equation 2-1).

$$n_{(t+1)} = \boldsymbol{A}n_t \qquad [2\text{-}1]$$

In this equation $\boldsymbol{A}$ is the population projection matrix which is made up of vital rate estimates. The goal of matrix modelling is to develop the population projection matrix such that

$$\boldsymbol{A}n = \lambda n \qquad [2\text{-}2]$$

where λ is the dominant eigenvalue of the matrix and the best estimate of the population growth rate (Caswell 2001). The growth rate calculated indicates the growth projection of the population (increasing, decreasing or stable), based on a specific time point (Caswell 2001). In addition, demographic models can be used for perturbation analysis which allows "what if" questions to be asked to determine how changes in vital rates would change population growth rates (Davis and Liebman 2003) (See Section 2.3.2). Incorporation of demographic modelling into agriculture and weed management methods could be used to develop methods which specifically target impactful life cycle stages, methods which will have the biggest overall impact on population growth rate, or to spread control methods over an organism's life cycle to help prevent the evolution of resistance (Davis et al. 2006, McEvoy and Coombs 1999).

2.3.1. Development of a matrix model

Matrix model development begins with describing the life cycle of the model organism, i.e. a plant, by breaking it into measurable growth stages. Plants transition between these stages throughout their life cycle. Vital rates measure survival of individuals through a certain time-step, as well as measuring reproduction and creation of new individuals (de Kroon et al. 2000). Vital rates can be affected by multiple transition steps throughout the life cycle. Knowledge of the lower level parameters (seedling survival, seed bank survival, etc.) allows one to determine the vital rates, and through the vital rates determine the population growth rate (λ) (de Kroon et al. 2000). By knowing the effect of a treatment on lower level parameters, one can determine the effect of that treatment on the overall population growth rate. Values for the lower level parameters in matrix models can come from previously reported values in the literature, or can be quantified in single or multiple experiments (Davis 2006). If values are not available, they can be estimated, however, this limits the accuracy of the model, particularly if the data is for a lower level parameter that highly impacts the overall population growth rate. Data coming from a single experiment for all transitions is most desirable as the covariance and error sources are consistent between parameters (Davis 2006).

In many cases, stage-structured or age-structured matrices are used for population demography (Caswell 2001). However, for annual species a one year time-step such as those typically used in the above mentioned matrices is not appropriate as the organism completes its life cycle within that timeframe (Caswell 2001). Periodic matrices, which use the product of submatrices for within-year vital rate evaluations, are considered the most effective way to describe annual species (Caswell 2001). Within periodic matrices the eigenvalue λ is independent of the within-year time frame the population is evaluated in; the evaluation can be done in the simplest time frame available (Caswell 2001, Davis 2006). For annual plants there is a single life-stage of seeds in the seed bank during the winter time; because it is a single life stage, the matrix collapses to a linear equation and can be solved using linear algebra. Davis (2006) provides an equation used to evaluate annual weed demographics. Model parameters include s_w (proportion of individuals surviving the overwinter seed bank), g (proportion of seed recruited from the seed bank), s_{sdl} (proportion of seedlings surviving to maturity), f (average fecundity per plant), s_{new} (proportion of newly shed seeds surviving), and s_s (proportion of seeds that survive the seed bank over the growing season) (Davis 2006) (Equation 2-3).

$$\lambda = (s_w \times g \times s_{sdl} \times f \times s_{new}) + [s_w \times s_s \times (1 - g)] \qquad [2\text{-}3]$$

The two components of the equation describe the above- and below-ground pathways of annual plants, respectively. To follow the above-ground pathway, an individual annual plant seed in the seed bank must survive the winter (s_w), emerge (g), survive to maturity (s_{sdl}), produce seed (f) and enter the seed bank (s_{new}). Alternatively, to survive the below-ground pathway an annual plant seed must enter the seed bank and survive the winter (s_w), survive the growing season in the seed bank (s_s), and not be recruited within the year (1-g). Survival of seeds in the seed bank over winter (s_w) occurs on both the above- and below-ground pathway and is the only parameter on both pathways. Both pathways consider the proportion of individuals surviving each pathway as well as the production of new individuals from the above ground pathway.

2.3.2. Perturbation analyses

Once a matrix model is developed, tools are available to further investigate the life cycle and the implications of the vital rates and lower level parameters. Perturbation analyses determine how the population statistics, typically population growth rate (λ), respond to vital rate or lower level parameter changes (Caswell 2000). Perturbation analyses can be used in a prospective or retrospective manner. Prospective analyses determine how much the population growth rate would change in response to a change in a vital rate or lower level parameter (Caswell 2000). A retrospective analysis would determine the variation in λ as a result of variation in lower level parameters or vital rates (Caswell 2000). In the case of determining how large an impact a new treatment or weed control method could have on overall population growth rate, or determining what impact a treatment would require to cause population decline, a prospective analysis is most appropriate (Caswell 2001).

Prospective analyses are conducted through the use of sensitivities and elasticities. Sensitivity determines the absolute change in λ as a result of an absolute change in a vital rate in the matrix model (de Kroon et al. 2000) (Equation 2-4).

$$\boldsymbol{s} = \frac{\partial \lambda}{\partial a_{ij}} \quad [2\text{-}4]$$

Elasticities are similar to sensitivities, however, they determine the proportional change in λ as a result of a proportional change in a vital rate in the matrix (de Kroon et al. 2000) (Equation 2-5).

$$\boldsymbol{E} = \frac{a_{ij}}{\lambda}\frac{\partial\lambda}{\partial a_{ij}} \quad [2\text{-}5]$$

Elasticities allow comparison of relative importance of transition steps as well as measure the contribution of a vital rate or lower level parameter to the population growth (de Kroon et al. 2000). The relative importance allows for identification of critical control points within a life cycle (Caswell 2000; de Kroon et al. 2000). While elasticities can provide a relatively robust prediction of the effect of an applied treatment, environmental variation, parameter variation, and a non-linear nature in the change of λ to lower level parameters means that predictions developed using elasticities can also be variable in their accuracy (de Kroon et al. 2000). Perturbation analyses are becoming more frequently used to aid in developing weed management strategies (Davis and Liebman 2003; Davis et al. 2003; Davis et al. 2004; Davis 2006). They can be useful for determining *a priori* how effective a new control method must be to cause a decrease in population growth (Davis et al. 2006). They can also identify which control agents are having the most effect on population growth rate of a pest and determine life cycle stages where additional control measures are required (McEvoy and Coombs 1999). In combination with cost effectiveness of control methods, development costs, and required efficacy levels, demographic models may contribute to the decision making process (Davis 2006), particularly for new technologies and management methods for agricultural weeds.

Retrospective analyses are often conducted in the form of a Life Table Response Experiment (LTRE) (Caswell 2001). These LTRE's allow comparison and contrasts of chosen treatments to associate the variation or lack of variation in a population growth rate with variation in the vital rates (Caswell 2001). It allows treatments to be investigated for which parameters are contributing to observed differences in population growth rates. The contributions from the parameters are calculated through determining differences in vital rates between two populations multiplied by the sensitivity of the population growth rate to that vital rate (Caswell 2001). LTRE results can be used to determine where treatments or new management technologies are impacting a plants life cycle, and if those treatments would be beneficial additions to an integrated weed management strategy, while also identifying life cycle stages where further management tactics would be beneficial (Davis et al. 2003).

2.4. Alternative Weed Management Methods

Diversity and redundancy in management techniques is critical to successful long-term management of any weed species (Liebman and Gallandt 1997). Any strategy used alone exerts a selection pressure that can result in resistance when there is genetic variation (Liebman and Gallandt 1997). Barret (1983) reported on barnyard grass (*Echinocloa crus-galli* var. *oryzicola*) evolved to be indistinguishable from rice crops as a result of selection pressure from hand-weeding; the physical similarity was an avoidance of control by hand-weeding, and essentially "resistance". Use of integrated weed management as defined above does not require herbicide elimination from weed management strategies, but an increase in the total number and diversity of strategies used (Buhler 2002; Harker and O'Donovan 2013; Liebman and Gallandt 1997). For producers to have these options available, research into novel and diverse management strategies must occur (Buhler et al. 2000; Harker and O'Donovan 2013).

By definition, integrated weed management incorporates physical, biological and cultural methods of weed control with chemical or herbicidal methods, as well as preventing the establishment of new weed populations. There is significant research occurring on developing weed management methods including autonomous weed control (Young et al. 2017), abrasive grit management (Forcella 2012), and rotations and competitive crops (Harker et al. 2016) among many other weed management techniques. Much of this research has been a response to increased weed resistance to herbicides (Beckie et al. 2013a; Heap 2017). However, most weed control technologies, particularly herbicides, target weeds at the seedling stage. Considering critical period of weed control studies suggest early control and minimized duration of weed competition with the crop, this target of weed management is not surprising (Liebman and Gallandt 1997). However, control of weed seeds and the weed seed bank could potentially be an effective additional management target in combination with seedling control, as suggested by demographic modeling (Davis 2006). Additionally, as larger seed bank sizes are correlated with a higher risk of resistance (Bagavathiannan and Norsworthy 2012), management of the seed bank can assist in managing resistance risk and resistant populations. Buhler et al. (1997) reviewed research that suggested changes in the seed bank must be large to affect weed control efficacy. Modelling has also indicated that seed control tactics will likely be most successful on species with modest fecundity and limited seed bank persistence (Davis 2006); high fecundity and high levels of persistence allow the population a temporal buffer against control measures and unfavorable environments (Davis 2006).

2.4.1. Harvest Weed Seed Control

In Australia, where herbicide resistance incidence is the 2nd highest globally (Heap 2017), harvest weed seed control (HWSC) is being investigated and optimized as an addition to current weed management tactics (Walsh et al. 2013). HWSC targets seed bank inputs of mature weeds at crop harvest (Walsh et al. 2013), rather than the seedling stage of weeds which is the primary target of herbicides. HWSC does not manage seeds which already reside in the seed bank, the target life-stage discussed above; however, it does target inputs into that life-stage through targeting s_{new}, the survival of newly shed seed as defined in Section 2.3.1. HWSC could be particularly effective in managing the establishment of herbicide resistant weed populations as weeds that survive in-crop herbicide applications are the same individuals setting seed (Buhler et al. 2000; Walsh et al. 2017a). If resistance mechanisms are responsible for those individuals' survival, preventing seed bank inputs from those individuals could help to minimize the proportion of resistance in subsequent generations. HWSC incorporates an additional management method which reduces selection pressure on any one management method such as herbicides, and is employed at a different life cycle stage than most other management methods.

HWSC is not suggested as a solitary weed management technique but is especially useful in systems with established herbicide resistant weed populations, when combined with typical integrated weed management practices. Australian producers combining HWSC and herbicide applications have reduced one of their most problematic weeds, annual ryegrass (*Lolium rigidum* Gaud.), to 0.5 plants m^{-2} from 5-7 plants m^{-2} with herbicides alone (Walsh and Powles 2014a). In the final year of a 27 year study (11 years with IWM), annual ryegrass populations were reduced from 170 m^{-2} with wide row spacing and no burning to 0 m^{-2} when narrow row spacing, herbicides and HWSC were combined (Borger et al. 2016).

In order for HWSC to be effective, plants must retain their seeds at the time of harvest (Walsh and Powles 2014b) and must produce their seeds at a height from which they can be collected by harvest operations (Walsh et al. 2016). As some species lose approximately 1% of their seed each day, time of harvest has a large influence on the number of weed seeds available in a field (Walsh and Powles 2014b). Seed retention is also likely to vary with species, agro-ecoregion and climatic conditions (Barroso et al. 2006; Petzold 1956; Shirtliffe et al. 2000). Seed retention of problem weeds has not been well investigated outside of Australia where these control methods began. Additionally, while height of seed production may not be a concern for relatively tall and erect weeds, twining or short statured weeds like wild buckwheat (*Polygonum convolvulus* L.) or shepherd's purse [*Capsella bursa-pastoris* (L). *Medik*] respectively, may have seed production at heights restrictive to HWSC efficacy. Weeds of these growth habits have not been well studied for their suitability for control with HWSC methods. Reliance on HWSC alone would lead to evolution of resistance in weeds through selection of early seed shed biotypes or seeds produced below a collectible height; continual selection of early maturing wild radish (*Raphanus raphanistrum* L.) can lead to a shift in flowering and maturity time (Ashworth et al. 2015).

A number of HWSC methods have been investigated for field use, primarily in Australia, with limited testing in the United States (Norsworthy et al. 2016; Schwartz et al. 2017). Some of these methods provide equivalent control levels (Walsh et al. 2017a), while others have not yet been scientifically tested as described below. However, while the methods were equivalent, the overall population control between field tests ranged from 37-90% with variability attributed to seed production and size of the established seed bank (Walsh et al. 2017a). Additional factors such as climatic conditions, species biotype and crop competition may also have affected the number of seeds available to the HWSC methods, and therefore overall efficacy. While control of seeds that enter the combine can be > 95%, typical estimated population control values are 60% (Walsh et al. 2017a), although this will vary based on climate, species, size of the established seed bank, as well as the efficacy with which the HWSC method is conducted. Adoption of HWSC methods in Australia has become widespread, with 43% of growers currently using one of the methods (Walsh et al. 2017b). Adoption levels are expected to double in the next 5 years with 82% of growers indicating that they expect to use a HWSC method in that timeframe (Walsh et al. 2017b). For adoption to occur in locations outside Australia, testing HWSC on new weeds in new locations is necessary to determine suitability and efficacy.

Spray-topping or crop-topping is a quasi-HWSC technique used just prior to harvest that involves spraying non-selective herbicides, typically glyphosate or paraquat, over the entire field to reduce seed production (Walsh and Powles 2007). Spray-topping effectiveness is weed stage dependent. When the staging is correct (typically when the weed is between late milk and soft-dough), spray topping has been shown to decrease weed seed production, weight and viability (Clay and Griffin 2000; Steadman et al. 2006). It has also been shown to decrease vigour of remaining viable weed seeds at emergence (Steadman et al. 2006). However, the effective timing to spray weeds may not correspond with an appropriate time for an application in the crop (Steadman et al. 2006). When treating with glyphosate, an early application can lead to detrimental effects on the crop seeds as well as the weeds (Baig et al. 2003). Spray topping at correct timings or with incorrect pre-harvest intervals may also increase herbicide residues in harvested crop seeds at higher than acceptable levels. In addition, spray-topping includes another herbicide treatment in the year's rotation, which leads to increased selection for herbicide resistance. Many Canadian producers apply non-selective herbicides pre-harvest, but typically for harvestability effects rather than weed management. While spray-topping can be a useful tool for weed management, the additional herbicide treatment makes it unique amongst the HWSC methods, which are not typically chemical reliant. This method may also not solely target the s_{new} life cycle stage, but may also target fecundity and actual seed production depending on application timing. It is considered here because it is a weed management method that targets seed bank inputs; however, it is unique from the other HWSC methods and was not truly developed within the HWSC paradigm.

Chaff collection has been recognized as a method to limit weed seed bank inputs at harvest (Olfert et al. 1991; Shirtliffe and Entz 2005; Walsh and Powles 2007). The technique involves pulling a cart behind the combine at harvest to collect chaff and weed seeds. Collected material is then dumped in piles and either burned or used for livestock feeding (Walsh et al. 2013). When tested, this method collected the majority of weed seeds that entered the harvester, enabling further management to be imposed (Walsh et al. 2013). Equipment costs, as well as the need for post-harvest management of the residues (burning or grazing), the decrease in harvest speed and the increased labour requirements particularly for chaff pile burning have limited producer uptake of this method of HWSC, even though it is effective (Australian Herbicide Resistance Initiative, 2014). In addition, initial problems with the design of the chaff cart, particularly related to the blower system between the combine and the cart itself, limited adoption. Adoption has increased again in recent years due to a redesign of the chaff carts which has resulted in higher incorporation of straw into the chaff fraction; this increases oxygen levels in the piles which shortens the time requirement for burning (L. Turner, personal communication). In addition, producers are concentrating chaff dumps in single or limited areas of the field and creating fire breaks around that area (L. Turner, personal communication). This limits the risk of fire escapes and concentrates burning and any consequential negative effects in one area of the field (L. Turner, personal communication). Chaff carts are currently used by 3% of Australian growers, less than other HWSC methods, however this proportion is expected to increase to 10% in the next five years (Walsh et al. 2017b). While chaff carts were first developed in Canada, there has not been a resurgence in the use of the methodology. Weather conditions limit time to burn chaff dumps as well as promote a higher risk of fire escapes than in Australia, restricting the usability of chaff carts and chaff burning. Mixed farm operations would be well suited to chaff cart use. However, the added equipment expense along with additional fuel expenses for towing chaff carts has limited producer interest, particularly without the current herbicide resistance situation being viewed as critical by most western Canadian producers.

Another HWSC method, baling chaff directly from the combine, has been used in Australia, but its implementation has been limited. Currently, 3% of Australian growers are using the bale direct method, with a minimal increase of 1% expected over the next five years (Walsh et al. 2017b). Direct baling involves transfer of the chaff and straw from the back of the combine into a baler pulled directly behind (Walsh et al. 2013). This has proven to be effective in controlling 95% of weed seeds (Walsh and Powles 2007). After baling, the bales can be converted to pellets and used in the live sheep export trade (M. Walsh, personal communication). It is believed that the heat and pressure used during the pelletizing process renders the weed seeds unviable or they will be damaged by digestion (M. Walsh personal communication). Devitalization by animal digestion, however, is species specific and not effective for all weeds (Blackshaw and Rode 1991; Buhler et al. 1997). Additionally, viable seeds could potentially be transported relatively long distances when bales are transported for feed, particularly if seeds are lost during transportation. This is not a common weed control technique due to the limited market for bales (Walsh et al. 2013, Australian Herbicide Resistance Initiative 2014). It has however, had a small level of adoption in Pullman, Washington, USA (M. Walsh personal communication).

Narrow windrow burning is another HWSC technique that is being implemented in Australia. This is the most commonly used HWSC method, with 30% of Australian crop producers using the practice with 46% expected to have adopted it in the next 5 years (Walsh et al. 2017b). It involves the collection of the chaff and straw into a narrow windrow during harvest through producer designed combine chutes that concentrate the residues into 50-60 cm windrows (Walsh and Powles 2007). Residue concentration increases burning temperatures for an extended period of time which more effectively controls weed seeds than lower temperatures or shorter burns (Walsh and Powles 2007). Temperatures of at least 400 C are required for a 10 s time period for an effective kill of annual ryegrass (Walsh and Newman 2007). Producers typically try to induce a slow, hot burn by burning on cooler days and with a wind perpendicular to the windrows (M. Walsh personal communication). In addition, producers typically are introduced to burning by burning canola and pulse residues which are less likely to lead to fire escapes as they usually produce less residue (M. Walsh personal communication). The concentration of the chaff in windrows limits the amount of standing stubble removed from the field during burning, which decreases the erosion risk typically involved with burning stubble residues (Walsh and Powles 2007). This HWSC method has been shown to be highly effective on annual ryegrass and wild radish (Walsh and Newman 2007). However, barley fields and high yielding fields of wheat with large amounts of residue are high risks for fire escapes (Walsh 2013). In addition, burning the residue also removes the nutrients that would return to the soil from the residue (Walsh and Newman 2007). Adoption of this method in western Canada is unlikely due to the high risk of fire escapes during the dry autumn season, higher yielding crops leading to larger residue volumes to burn, and the limited time for this type of procedure post-harvest and pre-seeding.

Other HWSC techniques used in Australia have not yet been scientifically evaluated for efficacy (Australian Herbicide Resistance Initiative 2014). Chaff decks divert the chaff fraction on to tramlines where the weeds are left to decompose naturally, and are a practical option for producers operating controlled traffic farming systems (Australian Herbicide Resistance

Initiative 2014). Controlled traffic farming systems are already operating on a tramline system and the tramlines are the least productive part of the field. Even prior to scientific evaluation, this technique is used by 7% of Australian growers with an expected increase to 15% of producers in the next 5 years (Walsh et al. 2017b). Another new technique is the use of narrow windrow rotting where the chaff fraction is diverted into a windrow and the weed seeds are left to rot (Australian Herbicide Resistance Initiative 2014). This eliminates the need to burn but may not be as effective at limiting seed viability. Evaluation of these methods is required to determine their viability as weed control methods, both in Australia and elsewhere. The limited use of controlled traffic farming systems in Canada limits the practicality of chaff decks. Additionally the climate in Canada may not be as conducive to decomposition as that of Australia due to the cold winter season following Canadian harvest rather than the hot summer season of Australia.

2.4.1.1. Harrington Seed Destructor and Seed Terminator

One of the most recent advances in HWSC methods is the invention of the Harrington Seed Destructor (HSD) in Australia. The HSD, developed by producer Ray Harrington, is a system pulled behind the combine that shuttles the chaff fraction into a cage mill which impacts and devitalizes seeds (Walsh et al. 2012). Walsh et al. (2012) tested the HSD under commercial harvest conditions and found that it controlled up to 99% of tested weed seeds (Walsh et al. 2012). In addition, after the chaff fraction has passed through the mill, the residues are released back to the soil, so there are no detrimental effects of chaff removal from the field (Walsh et al. 2012). Australian tests also indicated that the chaff volume being processed does not have a detrimental effect on weed seed control (Walsh et al. 2012). However, seed size affects the impact energy and may affect efficacy; small seeds may not be controlled to the same extent due to a lower impact energy from lower mass (Berry et al. 2015). Additional seed and crop factors such as seed shape, seed coat/external protrusions, moisture content, and chaff type may also impact weed control (Berry et al. 2015). Unlike other methods of HWSC, use of the HSD does not require additional residue management actions such as burning (Walsh 2013).

The HSD is commercially available in Australia (Walsh et al. 2013) but adoption has been limited due to the size and towing requirements of the machine, and the purchase cost of approximately $200,000 CAD (M. Walsh, personal communication). Currently < 1% of Australian producers use the HSD with adoption expected to increase to 7% in the next five years (Walsh et al. 2017b). Interestingly, 29% of Australian producers would prefer to use the HSD as a HWSC method in the next five years with few doing so as a result of the cost and a perception that the technology is unproven (Walsh et al. 2017b). However, an integrated version of the HSD that is built directly into combines has recently been released (Australian Herbicide Resistance Initiative 2016; de Bruin Engineering 2017). This integrated Harrington Seed Destructor (iHSD) had a limited release in 2016 and a larger scale, full release is planned for 2017 (Australian Herbicide Resistance Initiative 2016; de Bruin Engineering 2017). The iHSD further improves upon the HSD with a reduced cost of approximately $160,000 CAD (M. Walsh, personal communication), which is still restrictive for some producers.

Recently, a multi-stage hammer mill device called the Seed Terminator was also commercially launched in Australia (Seed Terminator 2017). This system works on a similar principle as the iHSD but uses a hammer mill impact system rather than a cage mill (Seed Terminator 2017). It provides the same benefits in comparison to the HSD and iHSD of returning residues to the soil to minimize nutrient loss while controlling weed seeds, and provides the convenience of the iHSD of being built into combines. The price of the Seed

Terminator is approximately $100,000 CAD (Seed Terminator 2017), lower than that of the iHSD. Stationary testing with the Seed Terminator resulted in > 90% weed control, while field scale testing is ongoing (Seed Terminator 2017). The introduction of this similar technology will likely lower the cost of the iHSD due to competition, which increases the potential market for these units (Walsh et al. 2017b). With the systems now integrated into combines, the primary reservation of Canadian producers will be cost. As herbicide resistance incidence continues to increase and fewer herbicide options are available, the financial feasibility of these machines increases. Use of either of these physical impact control systems in an integrated weed management system could slow the selection of further herbicide resistant weeds, aid in the management of weed populations, and minimize nutrient loss from incorporating HWSC methods into weed control tactics.

2.4.2. Weed Seed Bank Manipulation

Weed seeds germinate in the soil in response to cues such as moisture, temperature and light (Egley 1986). If weeds do not germinate, they remain dormant for future germination or experience fatal germination, microbial decay, predation or expiration (Fenner and Thompson 2005, Cousens and Mortimer 1995). Fatal germination or microbial decay could be mechanisms used to target the weed seed bank to impact population growth; they are potentially inducible through chemical stimulants (Fenner and Thompson 2005) or application of microbial decomposers (Kremer 1993). Scientists have in fact tried for many years to decrease the weed population in soils through use of chemical germination stimulants (Egley 1986). For example, ethylene has been successfully used to stimulate and control the germination of witchweed (*Striga asiatica*) (Egley 1986, Fenner and Thompson 2005). Other compounds have been tested with limited success, or success only under a narrow set of conditions (Egley 1986). Nitrogen has been shown to stimulate germination of wild oat plants under field conditions in the form of ammonium nitrate, particularly in combination with other stimuli such as moisture (Sexsmith and Pittman 1963). However, other species' germination was not affected by fertilizer application (Egley 1986). Some compounds in plant-derived smoke have been shown to have a stimulatory effect on germination (Papenfus et al. 2015; Stevens et al. 2007). Unfortunately, isolation of the compounds would be necessary as other molecules in smoke can also inhibit stimulation (Papenfus et al. 2015). The discovery of a consistent and effective chemical germination stimulant on multiple species would be an asset to producers as a novel method of weed management, particularly if combined with winter kill or other mortality inducing methods.

2.4.2.1. Fluridone

Fluridone, a group 12 phytoene desaturase inhibitor (Hamprecht and Witschel 2008) registered as Sonar, is an aquatic herbicide produced by SePro (Shaner 2014). Fluridone is a reversible non-competitive inhibitor of the phytoene desaturase enzyme (Hamprecht and Witschel 2008). Phytoene desaturase inhibitors inhibit the synthesis of carotenoids resulting in a build-up of toxic oxygen radicals that cause lipid breakdown and destroy membrane stability (Hamprecht and Witschel 2008). In addition to being used as an aquatic herbicide, fluridone was also tested in cotton, a tolerant crop, for weed control (Banks and Merkle 1979). Research into the compound for cotton declined due to residue carry-over to subsequent crops (Banks and Merkle 1979; Hill et al. 2016), availability of herbicides with better control spectrums, and the introduction of herbicide-resistant cotton cultivars. Fluridone is a persistent chemical with up to 20% of applied fluridone remaining in the soil 385 days after application (Banks et al.1979). However, Freund et al. (1994) has found that fluridone persistence was shorter in soils that had previous fluridone applications, indicating that multiple applications enhanced microbial breakdown, likely the primary method of degradation (Freund et al. 1994; Schroeder and Banks 1986). Fluridone, as a weak base herbicide, is affected by pH, with higher soil adsorption at low pH due to its presence in a cationic form (Weber 1980). This indicates that fluridone efficacy is affected by soil pH, as well as soil organic matter (Goggin and Powles 2014).

There has recently been a resurgence in fluridone research as a cotton herbicide (Braswell et al. 2016; Cahoon et al. 2015; Hill et al. 2016), but it has also been studied for its effects as a germination stimulant (Goggin and Powles 2014). Weed seed stimulation after application of fluridone was recorded on economically important weeds in Australia like *Lolium rigidum, Raphanus raphanistrum, Avena barbata,* and *Sisymbrium* spp. (Goggin and Powles 2014) when grown in pots. Field testing of fluridone germination stimulation was unsuccessful due to drought (Goggin and Powles 2014). After seed germination, herbicidal effects of bleaching (consistent with reported herbicidal effects) were observed on some seedlings followed by plant death (Goggin and Powles 2014). This study also indicated that field pea may be tolerant to fluridone (Goggin and Powles 2014). Fall applied fluridone having both germination stimulant and herbicidal effects may provide a new method of weed control in western Canada, particularly when combined with potential winter kill. However, phytotoxic residues are a concern. Phytotoxicity to crops may be manageable through split or repeated applications of fluridone due to the enhanced degradation on fluridone history soils (Freund et al. 1994; Goggin and Powles 2014). Fluridone efficacy on Canadian weeds has not been tested for germination stimulation but may provide an effective method to manipulate the weed seed bank.

2.5. Target Weeds in Western Canada

Weed management in western Canada is important to producers, as it is globally, particularly with the increased incidence of herbicide resistance. While it has not reached the notoriety of annual ryegrass in Australia or palmer amaranth (*Amaranthus palmeri* S. Wats.) in the southern United States, wild oat is the primary 'driver' weed (i.e., a species that receives primary management attention) in western Canada (see below). Other weed species are becoming more prevalent and problematic in western Canada such as false cleavers (*Galium spurium* L.) and volunteer canola (*Brassica napus* L.). These three species were selected as target weeds for this thesis. While many other weeds could have been included, these species represent 'driver' weeds and a diversity of life cycles and growth habits in western Canada.

2.5.1. Wild Oat

2.5.1.1 Biology

Wild oat is the most economically important weed in Canada, accounting for more crop yield losses and herbicide expenditures in western Canada than any other weed (Beckie et al. 2012). Every year over $500 million are spent on controlling wild oat in western Canada (Beckie et al. 2012). It is found across Canada and in most temperate or semi-arid cropping areas of the world (Beckie et al. 2012). It is a competitive weed, believed to be equally as competitive as wheat, and is particularly competitive for soil nitrogen (Beckie et al. 2012). Wild oat can reduce crop yields by as much as 70% (Beckie et al. 2012).

Wild oat produces between 20 and 1070 seeds per plant (Beckie et al. 2012). However, wild oat is prone to seed shatter and can lose over 50% of seeds from the panicle prior to spring annual crop harvest (Shirtliffe et al. 2000). It is estimated that wild oat will have shed 80% of its seed when wheat is direct harvested at 20% soil moisture, although this may be buffered by the potential for multiple cohorts to emerge temporally over the growing season (Shirtliffe et al. 2000). In contrast, early swathed crops such as canola could lead to 80% of the seed remaining on the wild oat panicle at harvest time (Shirtliffe et al. 2000). A recent estimate of wild oat seed shed was significantly lower than previous estimates with approximately 30% of wild oat seeds shed at the time of wheat and field pea maturity (Burton et al. 2016). Reasons for differences in wild oat seed shed estimates are not clear. Wild oat seed banks can be up to 2500 seeds m^{-2} and seeds can persist in the seed bank typically for 4-5 years (Beckie et al. 2012).

Resistant wild oat has been reported for a number of herbicide modes of action (Beckie et al. 2013a). In a recent survey of the Prairie Provinces, 44% of fields where wild oat was collected had a herbicide resistant wild oat biotype (Beckie et al. 2013a). Acetolactate synthase (ALS) inhibitor (group 2) resistant wild oat was reported in Manitoba, Canada, in 1994 (Heap 2017), and was subsequently reported in Alberta and Saskatchewan (Beckie et al. 1999). ACCase resistance is the most prominent resistance in wild oat, confirmed in 41% of surveyed fields where seeds were collected, and 28% of all surveyed fields (Beckie et al. 2013a). ALS-inhibitor resistant wild oats have been confirmed in 12% of fields where seeds were collected and in 8% of total surveyed fields across the Prairies (Beckie et al. 2013a). Resistant wild oat were also reported in this survey to group 8 (lipid synthesis inhibitor) herbicides in 8% of sampled fields. In addition, multiple-resistant wild oats were also reported to group 1+2, group 1+8, group 2+8 and group 1+2+8 (Beckie et al. 2013a). More recently a population was identified with resistance to group 1, 2, 8, 14 (Protoporphyrinogen oxidase inhibitors) and 15 (very long chain fatty acid elongase inhibitors) (Mangin et al. 2016). Herbicide resistant wild oat has been identified in 15 countries world-wide (Heap 2017) and is a potential high risk weed for evolution of glyphosate resistance in western Canada (Beckie et al. 2013b).

2.5.1.2. Abundance

Wild oat (*Avena fatua* L.) has been ranked as the 2nd most abundant weed in the Prairies since 1970, although its relative abundance has increased (Leeson et al. 2005). Wild oat is more commonly found in zero-till cropping systems when compared with conventional till (Beckie et al. 2012). Wild oat is a problematic weed in all major crops in western Canada (Leeson et al. 2005). Its continued dominance as a problematic weed throughout the decades indicates a challenge to which there is not yet a solution. The abundance combined with the prevalence of herbicide resistance and the additional high risk of being one of the next glyphosate resistant weeds indicates that wild oat will be continue to be a problematic weed for producers unless new management strategies are developed.

2.5.2. False Cleavers

2.5.2.1. Biology

False cleavers (hereafter referred to as cleavers) is an annual weed of the Rubiaceae family. It is seldom distinguished from *Galium aparine* and the literature often does not confirm which species is being investigated. Cleavers grows in most temperate climates and is adapted to relatively dry climates (Malik and Vanden Born 1988). Cleavers is a facultative winter annual which can confer a competitive advantage over crops (Malik and Vanden Born 1988). It is a common and competitive pest in wheat, canola and pea fields (Leeson et al. 2005). Cleavers have curved, hook-like spines on stems and bur-like seeds adapted for seed dispersal (Malik and Vanden Born 1988). The semi-prostrate, twining, climbing stems can cause crop lodging and harvesting difficulties, and seeds are difficult to remove from some crop seeds post-harvest (Malik and Vanden Born 1988). Cleavers can produce up to 3,500 seeds per plant (Malik and Vanden Born 1988), leading to high seed bank inputs if not controlled. Cleavers tends to have little primary dormancy but can typically be found in the seed bank for up to 3 years (Malik and Vanden Born 1988). Ingestion by animals does not limit the viability of the seeds (Malik and Vanden Born 1988). Cleavers have shown high seed retention in west-central Saskatchewan in both small plots (95%) and producer fields (96-98%) at wheat, canola and pea maturity (Burton et al 2016; 2017).

Cleavers have been reported with herbicide resistance since 1998 when resistance to ALS-inhibitors was reported in Alberta (Hall et al. 1998) and subsequently reported in Saskatchewan and Manitoba (Heap 2017). In addition, the initial resistant population also exhibited multiple resistance to the auxin-like herbicide quinclorac (Hall et al. 1998; Van Eerd et al. 2004). ALS-inhibitor resistant cleavers are becoming an increasingly significant problem with up to 17% of fields surveyed having resistant populations (Beckie et al. 2013a). In addition, cleavers is a high risk species for evolution of glyphosate resistance in some agro-ecoregions of western Canada (Beckie et al. 2013b).

2.5.2.2 Abundance

Cleavers is the 9th most abundant weed on the Canadian prairies (Leeson et al. 2005). It has steadily increased in abundance in western Canada since the 1970s when it ranked 43rd (Leeson et al. 2005). It is in the top 10 most abundant weeds in nearly all the major crops (Leeson et al. 2005) and is known to be a particular problem in canola and field pea. Cleavers seed is particularly hard to remove from canola seed as the seeds are a similar shape and size (Malik and Vanden Born 1988). Cleavers were the 7th weed in terms of relative abundance in Saskatchewan in 2014 – 2015, continuing the trend of increasing abundance (Leeson 2016). Increased abundance of cleavers combined with the potential continued evolution of herbicide resistance indicates that it will continue to be a problem weed in western Canada.

2.5.3. Volunteer Canola

2.5.3.1 Biology

Volunteer canola is an annual weed that establishes from shattering and harvest losses of domesticated canola crops (Cavalieri et al. 2016). Volunteer canola is found across Canada but is particularly prevalent in western Canada due to the abundance of domesticated canola crops each year (Gulden et al. 2008). Two year rotation frequency of canola alternated with wheat is the most common rotation in the Prairies (Beckie 2016). It is primarily an autogamous species although allogamy rates up to 47% have been reported (Gulden et al. 2008). The latter can be problematic due to the high proportion of genetically modified herbicide-resistant biotypes grown for crop, allowing multiple herbicide resistance traits to establish in the volunteer populations (Beckie et al. 2003; Hall et al. 2000). The number of seeds produced by volunteer canola is not well documented in the literature (Gulden et al. 2008). However, seed bank inputs from harvest losses of domesticated canola can range from 2500 to 6100 seeds m^{-2} (Cavalieri et al. 2016). Canola seed can be lost during swathing/windrowing procedures, as well as during combining as canola pods are prone to shattering when mature (Gan et al. 2008). Once in the seed bank, seeds can persist for at least 3 years, although longer periods have been suggested (Gulden et al. 2008). However, the number of volunteer plants decreases dramatically with each year after the canola crop (Gulden et al. 2008; Harker et al. 2006).

Most of the canola crops grown in Canada are genetically modified to be resistant to glyphosate or glufosinate, although there has been small market share for Clearfield (ALS resistant) varieties. There have also been triazine resistant cultivars (Gulden et al. 2008). There are no documented cases of naturally evolved herbicide resistance in canola (Heap 2017), however the resistance traits present in most volunteers leads to difficulty controlling them prior to crop seeding, and they can be difficult to control in subsequent crops.

2.5.3.2. Abundance

Volunteer canola was ranked as the 14th most abundant weed in western Canada when last surveyed across the Prairie Provinces (Leeson et al. 2005), but was 4th in relative abundance in the 2014 and 2015 survey in Saskatchewan (Leeson 2016). However, since the time of the initial survey, production of canola has increased from about 5 million hectares seeded (Casseus 2009) to over 8 million seeded hectares in 2016 (Statistics Canada 2016). The increased crop area also leads to a higher seed bank input area leading to volunteers the following year. In addition, as one of the most lucrative crops to produce (Casseus 2009), many producers will plant it consecutive years in a row to maximize profits, which can lead to an extensive seed bank. An increase in the cultivation of canola, along with the increased abundance and prevalence of herbicide tolerance has led to volunteer canola becoming increasingly problematic for Canadian producers. New management techniques would be highly valued by crop producers.

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Chapter Three: Suitability of Wild Oat (*Avena fatua*), False Cleavers (*Galium spurium*) and Volunteer Canola (*Brassica napus*) for Harvest Weed Seed Control in Western Canada[1]

3.1. Introduction

Increasing herbicide resistance in western Canada (Heap 2017) has increased the search for novel weed management techniques to add to current cropping systems. Three of the problem weeds in Western Canada are wild oat, false cleavers (hereafter called cleavers) and volunteer canola. Wild oat is a nearly ubiquitous weed with high rates of seed shatter, seed dormancy and a competitive nature (Beckie et al. 2012; Shirtliffe et al. 2000). Over $500 million per year is spent to control wild oat, but as the most herbicide-resistance prone weed in western Canada additional control options are needed (Beckie et al. 2012, 2013a, 2013b; Mangin et al. 2016). False cleavers' prevalence is increasing faster than any other weed in western Canada, (Leeson et al. 2005); it is difficult to control in many crops, has shown resistance to ALS inhibitors and quinclorac and is at high risk for selection of glyphosate resistance in the sub-humid regions of western Canada (Beckie et al. 2013b; Heap 2017). These characteristics make cleavers a priority for management by non-herbicidal methods. Canola is one of western Canada's most prominent crops; however, an average of over 4300 seeds m^{-2} are lost at harvest to the seed bank resulting in a large, herbicide-resistant (glufosinate or glyphosate) volunteer canola population (Beckie et al. 2003; Cavalieri et al. 2016; Hall et al. 2000). Increased abundance of volunteer canola (Leeson et al 2005; Leeson 2016), potential impacts of crop

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competition through difficult-to-manage volunteers, and high densities make volunteer canola another priority target for additional management options.

Harvest weed seed control (HWSC) is a new method of weed management that was evaluated and optimized in Australia (Walsh et al. 2013). These technologies target weed seeds that are otherwise dispersed by harvesters, typically in the chaff fraction which is broadcast back on to the field through spreader systems (Petzold 1956; Shirtliffe and Entz 2005; Walsh and Powles 2007; Walsh et al. 2013). While HWSC methods are effective in controlling weed seeds in the chaff fraction (Walsh et al. 2012; Walsh and Newman 2007; Walsh and Powles 2007), their ability to decrease weed populations depends on seed retention of the target species (Walsh and Powles 2014) and canopy height at which the weed seeds are retained relative to crop harvest height (Walsh et al. 2016). However, these characteristics are likely to vary with species, climatic conditions and agro-ecoregions (Barroso et al. 2006; Petzold 1956; Shirtliffe et al. 2000). Adapting harvesting to more effectively harvest weed seeds may have detrimental effects on snow capture, avoidance of rocks, harvest efficiency and residue retention (Cutforth and McConkey 1997; McMaster et al. 2000; Špokas and Steponavičius 2010). Ideal target weeds would retain seeds until or past crop harvest above typical harvest heights. It is not known whether wild oat, cleavers and volunteer canola meet these ideal characteristics.

The objective of our study was to evaluate the suitability of wild oat, cleavers, and volunteer canola as targets for HWSC management through determination of their seed retention characteristics at three western Canadian sites. In addition, potential effects of crop species competition and crop seeding density on these characteristics were investigated.

3.2. Materials and Methods

This study was conducted over 2 years (2014 and 2015) at three locations: Lacombe and St. Albert, Alberta, and Scott, Saskatchewan. Four treatments of crop and seeding rate combinations were established in a randomized complete block design with four replicates to measure seed retention and height of seed retention as affected by crop species. Two crops, wheat ('Harvest'), and fababean ('Snowdrop'), were chosen for their variation in competitive ability and maturity dates. Pulse crops such as field pea and fababean are less competitive than a cereal crop like wheat (Harker 2001). However, fababean is also a longer season crop and is harvested later than wheat. Each crop was seeded on the same date in mid-May at 1x- or 2x-recommended seeding rates: 30 or 60 seeds m^{-2} for fababean and 200 or 400 seeds m^{-2} for wheat. Prior to crop seeding (same day or day prior), wild oat, cleavers and volunteer canola were cross-seeded at a depth just below the soil surface across the plot area, with each weed in a separate strip. Weed seeds were sourced individually at each site. Wild oat was seeded at 200 seeds m^{-2} in both years. Cleavers were seeded at 200 seeds m^{-2} in 2014 but at 400 seeds m^{-2} in 2015 at Scott and Lacombe due to low germination. Volunteer canola was a true F2 population without seed treatment used at all sites and was seeded at 75 seeds m^{-2}. Seeding rates were based on target weed densities of 15-20 plants m^{-2} based on seed viability, and typical observed self-thinning rates. At Lacombe, and at Scott in 2015, a ConservaPak (ConservaPak Seeding Systems, Indian Head, Saskatchewan, Canada) air drill with knife openers at 22.8-cm row spacing was used. In 2014, the Scott location was seeded using a hoe-drill with 25-cm row spacing. In both years, the St. Albert sites were established with a Fabro plot seeder (Fabro Enterprises Ltd., Swift Current, Saskatchewan, Canada) with 20-cm row spacing. Plot sizes in Lacombe both years and at Scott in 2015 were 4 x 12 m. At St. Albert both years and at Scott in 2014, plot size was 4 x 6 m. For each weed at Lacombe and at Scott in 2015, there was 4 x 4 m of area from which to collect data, while at St. Albert and at Scott in 2014 the area was 4 x 2 m. All trials were established by direct seeding into barley (*Hordeum vulgare* L.) stubble with the exception of St. Albert in 2014, which was seeded into canola stubble to limit the establishment of cleavers at that research location to where they were already present. Fertilizer N, P, and S, were applied based on soil test recommendations.

After plant emergence, crop and weed densities were counted. Once weeds reached the reproductive stage (seed formation visibly beginning on plant), seed shed was assessed by placing shatter trays between the crop rows in the plots. Shatter trays measured 25.5cm x 15.5cm and were lined with mesh for water drainage. Two shatter trays were placed in each weed species strip in each plot for a total of six shatter trays per plot. These trays were checked twice weekly for an approximate 2-month period (end of July/beginning of August to end of September/beginning of October) and shed seed was collected, air-dried and counted. It is possible that seed predation occurred during the collection period; twice weekly collections mitigated some of that risk. Germination tests on shed seeds were conducted following the protocol used by Burton et al. (2016) beginning in the year following the field season (i.e. 2015 for the 2014 field season) to allow for dormancy breakage. A maximum of 75 seeds per shatter tray were evaluated for germination/viability (three replicates of 25 seeds each if possible). Germinated seedlings were counted for 2 wks and considered germinated at visible radicle emergence. Ungerminated seeds after that period were tested for viability using a press test (Sawma and Mohler 2002; Ullrich et al. 2011).

Based on crop maturity, weeds were harvested at three timings: in wheat and fababean at wheat swathing timing (hard dough stage; BBCH=87), and in wheat at direct-harvest timing (BBCH=99) and in fababean at direct-harvest timing (BBCH= 89/97). Weeds were harvested by cutting at ground level from a 0.5 m^{-2} quadrat in each weed strip of plot and sectioned into four heights: 0-15, 15-30, 30-45 and ≥ 45 cm above ground level. A threshold height of 15 cm for cereals and oilseeds has been used in previous seed retention studies (Walsh and Powles 2014; Burton et al. 2016), with seeds produced below this height considered to be non-collectable. While some pulse crops are harvested close to ground level (i.e. field pea, *Pisum sativum* L.; lentil, *Lens culinaris* L.) to collect as many pods as possible, fababeans are also harvested 15 cm above ground level. Samples were dried at low heat (≤ 30 C) until dry weight stabilized, weighed, threshed and cleaned. Seeds at each height interval were counted.

Using the number of seeds shed and number of seeds retained, the average total number of seeds produced m^{-2} was determined and used to calculate the percentage of seeds retained over time. Growing degree days (GDD) were calculated (Equation 3-1), with a base temperature of 5 C, for each shatter tray collection date and used as the independent variable for further analyses.

$$GDD = \sum \left(\frac{T_{max} + T_{min}}{2} \right) - T_{base} \qquad [3\text{-}1]$$

3.2.1. Statistical analysis

SAS 9.4 (SAS Institute 1995) was used for all analyses. The MEANS procedure was used to determine weed density means, standard errors, and ranges. For seed retention, PROC GLIMMIX was used with treatment (fababean 1x, fababean 2x, wheat 1x, wheat 2x), site-year and their interactions considered as fixed effects, and replicate as a random effect to determine which data could be pooled, using a beta error distribution. Due to a significant site-year*treatment interaction, data were not combined across site-years.

Wild oat and cleavers percentage seed retention were regressed against GDD using one of four models: logistic, segmented, quadratic, and linear, while segmented or linear regressions only were applied to canola data. PROC NLMIXED was used to conduct nonlinear regression with a logistic model (Equation 3-2).

$$Y = D + \frac{(A-D)}{\left\{1+exp\left[B*log\left(\frac{x}{G}\right)\right]\right\}} \qquad [3\text{-}2]$$

where Y is % of seeds retained, D is the upper limit, A is the lower limit, B is the slope, x is GDD, and G is GDD where 50% of seeds are lost. For logistic regressions, bounds were imposed on A and D to be ≥ 0 and ≤ 100, respectively.

PROC NLMIXED was also used for segmented line regression (Equation 3-3)

$$Y = L + U*(R-x) + V\times(x-R)\times(x-R) \qquad [3\text{-}3]$$

where Y is % seed retained, L is the asymptote, U and V are slopes of the first and second line segments respectively, x is GDD and R is the breakpoint GDD value. In two cases (see Results and Discussion), the second line segment was evaluated as a quadratic; in this situation an additional (x-R) term was added to the end of the equation (Equation 3-3).

PROC REG was used for quadratic regression (Equation 3-4)

$$Y = Ax^2 + Bx + C \qquad [3\text{-}4]$$

where Y is % seed retained, x is GDD, A and B are slope values and C is the intercept. PROC REG was also used for the linear model (Equation 3-5)

$$Y = Mx + B \qquad [3\text{-}5]$$

where Y is % seed retained, x is GDD, M is slope, and B is the intercept.

For all regression models, a parameter contrast was used to determine if seeding rate was significant ($\alpha = 0.05$). Where seeding rate was non-significant, data were pooled within species. A single regression model is presented for each site-year, crop and weed based on adjusted R^2 comparisons between all regressions for that data set; the model with the highest adjusted R^2 value is presented (Littel et al. 2002).

Height of seed retention was analyzed in PROC GLIMMIX with a Gaussian error distribution because of failure to converge with a beta error distribution. Fixed effects for each species included site-year, height, harvest timing, and treatment (crop and seeding rate); replicate was a random effect.

Seed viability was analyzed for each species using PROC REG (Equation 3-5). Analysis was conducted across site-years and treatments. Due to the sample size variability within site-years and treatments for each GDD, trends in viability versus GDD across site-years and treatments are discussed.

3.3. Results and Discussion

Weed and crop populations established well at all sites. However, weed densities in 2015 (Table 3-1) may have been influenced by the widespread drought across the Canadian prairies that year (Agriculture and Agri-Food Canada 2016). For May through July in 2015, Lacombe had 82% of long term average precipitation, St. Albert 70% and Scott 56% (data not shown). Wild oat populations ranged from 19 to 128 m^{-2} and cleavers populations from 8 to 213 m^{-2} (Table 3-1). Volunteer canola populations ranged from 13 to 53 m^{-2}; one notable exception was 512 m^{-2} in St. Albert in 2014 due largely to volunteers from the preceding crop.

3.3.1. Seed Retention.

Seed retention decreased as GDD increased. Seed retention over time varied by species, site-years and treatments. Location and the location by treatment (crop and seeding rate) interactions were significant for all three species ($p \leq 0.0001$ in all cases). Why retention over time differs within a species between site-years is unclear, although the range of variation becomes apparent by conducting the experiment for multiple site-years.

Wild oat had consistently early seed shed (Figure 3-1). Retention at the time of wheat swathing averaged 56% (range 20-72%). Seed retention at wheat and fababean direct-harvest timings averaged 33% (5-58%) and 30% (11-41%), respectively. However, retention was variable between sites and years. Although not consistent for every site-year, wild oat in wheat plots generally had lower retention than wild oat in fababean plots (Figure 3-1). This may be related to the increased competition faced by wild oat in wheat when compared to fababean leading to an increased rate of maturity (Harper 1977). Seeding rate effects on seed retention were typically not significant, but where significant did not show decreased retention with increased seeding rate as hypothesized. The majority of seed retention over time responses were best described by a logistic model (Appendix A Table A-1) rather than the sigmoidal response reported by Shirtliffe et al. (2000), suggesting variability in retention over time. The estimates for retention in wheat are consistent with those of Shirtliffe et al. (2000) but lower than Australian and recent Canadian estimates at wheat harvest (Walsh and Powles 2014; Burton et al. 2016). This may be due to different wild oat species or genotypes/ecotypes, use of different crop cultivars, seeding dates, seeding rates, row-spacings or fertility regimes. Additionally, both high and low wild oat seed retention has been observed in hundreds of prairie crop fields surveyed near harvest time (H. Beckie, personal communication). Variability in wild oat seed retention should be expected given the plasticity of the species, potential differences in wheat cultivar maturity and competitiveness, and the rapid change in seed retention close to maturity. Although a wide range of retention levels was observed at each harvest timing in our study, even at the earliest collection date (wheat swathing), greater than 40% of wild oat seeds were unavailable for HWSC. Demographic models have indicated that more than 80% of wild oat seeds would need to be retained and controlled for HWSC to be effective in reducing wild oat populations (Tidemann et al. 2016); based on the measured retention values, high levels of HWSC efficacy on prairie wild oat populations are unlikely. Burton et al. (2016) also concluded that wild oat may not be well controlled by HWSC methods.

Cleavers seed retention was highly variable among site-years (Figure 3-2). At wheat swathing, cleavers retention averaged 84% (range 41-99%). St. Albert is a unique site with lower retention values in both years at all timings although the reason for this retention pattern is unclear. At wheat direct-harvest, retention averaged 62% (8-94%); at fababean direct-harvest, retention averaged 50% (3-92%). Best fit regression models differed by site-year, and included logistic, segmented line, quadratic and linear responses (Appendix A Table A-2). A unique case is Lacombe in 2015 where the lower line segment in the segmented regression was best fit by a quadratic model for both wheat and fababean. The variability in cleavers retention values and patterns makes it difficult to predict the effect of HWSC on managing cleavers populations. At the Scott and Lacombe locations, the high seed retention levels at wheat swathing indicate that managing cleavers populations by swathing versus direct-harvesting may increase the efficacy of HWSC. Seeding rate was only significant in affecting seed retention in fababean. However, there is no consistent trend among site-years in terms of seeding rate effects (Figure 3-2). Seed retention of cleavers in wheat from this study is lower than the percentage of cleavers seed retained measured by Burton et al. (2016). The reason for this discrepancy is unclear, but highlights variation in seed retention of different populations as influenced by different agronomic factors. Based on the measured retention values, HWSC efficacy on cleavers will be highly variable and cropping system dependent, but more effective than on wild oat.

Canola seed retention was the greatest of all the species, with very low percentages of seeds shed over the study period for any site-year (Figure 3-3). Best fit regression models were primarily linear for canola grown in wheat and segmented for canola grown in fababean, however R^2 values were relatively low due to minimal seed losses (Appendix A Table A-3). Seed retention over time among crop treatments was similar during the time both crops were sampled, with the decrease in retention in fababean primarily occurring after wheat direct-harvest timing (Figure 3-3). Canola seed retention at wheat swathing averaged 99% (range 97-100%). At wheat and fababean direct-harvest, retention averaged 98% (89-99%) and 94% (79-99%), respectively. The lowest retention was at St. Albert in 2014, when the site was seeded on canola stubble and had a dense population of volunteer canola. The increased competition may have resulted in an increased rate of canola maturity and therefore increased seed shed. With the exception of St. Albert in 2014, canola seed retention was >90% and often >95%. The lack of seed shed for volunteer canola and a low degree of variability in seed retention over time highlights the potential for volunteer canola to be managed with HWSC.

3.3.2. Height of Seed Retention.

For wild oat and canola, the four-way interaction of site-year, treatment, harvest timing, and height was significant ($p<0.0001$). The three-way interactions of site-year, treatment and height, and site-year, timing and height were significant for cleavers ($p<0.0001$ for both). Percentage of seeds at harvest for fababean and wheat were evaluated at their respective direct-harvest timings; percentages at swathing are from the wheat swath timing for both species. Across all species, seed retention was more highly concentrated in the upper canopy in 2014 than in 2015 (Table 3-2); this is likely related to drought effects on both crop and weed heights in 2015 leading to shorter plants, later emerging plants, and more seeds present throughout the canopy. The dispersion of seeds in the canopy was particularly evident for cleavers when comparing 2014 versus 2015 results. Wild oat and canola seeds were both retained high in the crop canopy with 1 and 0% of their seeds considered non-collectable, respectively. For cleavers, an average of just under 10% were considered non-collectable, leaving over 90% of seeds in the collectable fraction. Among all treatments and site-years, a maximum of 29% of seeds was non-collectable, leaving 70% available for HWSC in a "worst-case" scenario. There is a trend in wild oat and canola for a greater spread of seeds through the canopy at direct-harvest compared to swathing, particularly in 2015. This may be due to maturation of tillers/branches and later emerging plants. Cleavers does not show the same pattern, likely due to seed maturity and loss occurring from the ground up for this species (Malik and Vanden Born 1988). Overall, height of seed retention does not appear to pose a limitation for HWSC for these species.

3.3.3. Shed Seed Viability.

The viability of shed seeds collected in shatter trays was highly variable. While there was a significant regression for increasing viability as GDD increased (data not shown), adjusted R^2 were low for all species (wild oat=0.02, cleavers=0.14, canola=0.19). For nearly every collection timing for every site year, viability of seeds ranged from 0-100% (data not shown). This high variability, combined with small sample sizes for some treatment and GDD combinations, led to a low ability to determine trends and treatment effects. However, because viability measurements up to 100% were recorded for nearly every timing and weed combination with high variability in the measurements, assuming seeds are viable minimizes the risk of overestimating efficacy. Therefore, each seed shed before HWSC is implemented could potentially contribute to the following year's population; each seed lost prior to harvest should be assumed to decrease the efficacy of HWSC.

Based on percentage seed retention and plant height of seed retention, wild oat, cleavers and volunteer canola can be classified by their potential to be controlled by HWSC techniques. While height of seed retention does not hinder control of wild oat, poor seed retention at harvest limits HWSC potential. As the 'driver' weed most likely targeted for control and the most important herbicide-resistant weed in western Canada (Beckie et al. 2013b), an inability to control wild oat effectively will be a significant challenge in the acceptance and adoption of HWSC techniques in the Canadian Prairies. Although the potential for HWSC of wild oat may be limited, field research is needed to determine the long-term impact of these technologies on prairie populations.

High variability across site-years in pattern, timing and overall seed loss makes the effect of HWSC on cleavers population abundance difficult to predict. Across all site-years, collection of cleavers at wheat swath timing substantially increased the percentage of retained seeds. Inclusion of swathing in cropping systems may be an effective way to manage cleavers through use of HWSC.

With most of the seeds retained high in the canopy and a high level of seed retention, canola volunteers are likely to be managed effectively with HWSC technologies. Considering high seed losses are known to occur once canola enters the combine, HWSC is likely to be an important addition in managing volunteer canola populations, particularly in subsequent broadleaf crops, and for minimizing genetic co-mingling between canola cultivars.

HWSC suitability ranking of tested species is canola > cleavers > wild oat. While HWSC will have a fit for specific weed species in western Canada, it is important to consider the selection pressure being imparted by these technologies. HWSC techniques will select for individuals in the populations with seeds maturing/retained below 15 cm, earlier maturation and earlier seed loss (Ashworth et al. 2015). This should not impede the adoption of HWSC in western Canada, but should continue to encourage research and development into alternate control strategies and producer use of integrated weed management systems.

Table 3-1. Wild oat, cleavers, and canola densities at each site-year (n=4). Standard errors are in parentheses.

Site-year	Density		
	Wild oat	Cleavers	Canola
	Plants m^{-2}		
Lacombe 2014	83 (5)	30 (4)	53 (3)
Lacombe 2015	46 (4)	10 (1)	36 (2)
Scott 2014	128 (7)	8 (1)	43 (2)
Scott 2015	19 (2)	30 (6)	13 (1)
St. Albert 2014	112 (25)	213 (25)	512 (33)[a]
St. Albert 2015	24 (4)	16 (2)	23 (2)

[a] This location was seeded on canola stubble. High canola populations are related to volunteers from the preceding crop.

Table 3-2. Percent of seeds retained in 0-15 cm and ≥45 cm , listed by site-year, treatment and harvest timing. Standard errors are given for each species; different standard errors due to missing data are given in parentheses (applies to whole treatment). Locations are Lacombe (La), Scott (Sc) and St. Albert (StA). An average for the % of seeds across site-years and treatments is shown at the bottom. The treatments are defined as follows (Crop-Seeding rate): 1= Fababean-1x, 2= Fababean-2x, 3= Wheat-1x, 4= Wheat-2x.

		Wild Oat SE=2.4				Cleavers SE=6.7				Volunteer canola SE =1.4			
		Swath		Direct Harvest		Swath		Direct Harvest		Swath		Direct Harvest	
Site-yr	Trt	0-15	≥45	0-15	≥45	0-15	≥45	0-15	≥45	0-15	≥45	0-15	≥45
La14	1	0	100	0	100	6	79	5	75	0	100	0	100
	2	0	100	0	100	15	56	6	63	0	100	0	100
	3	0	100	0	98	17	42	3	81	0	100	0	100
	4	0	100	0	98	13	70	2	88	0	100	0	100
Sc14	1	0	99	0	100	1	89 (7.7)	3	78	0	100	0	100
	2	0	99	0	99	6	66	4	81 (7.7)	0	100	0	100
	3	0	100	0	99	2	85	8	75	0	100	0	100
	4	0	99	0	99	6	57	9	36	0	100	0	100
StA14	1	0	100	0	100	8	57	5	66	0	100	0	99
	2	0	100	0	100	5	55	7	52	0	100	0	99
	3	0	99	1	99	7	64	0	48	0	100	0	100
	4	0	96	0	100	3	73	0	61	0	100	0	99
La15	1	0	96	0	81	23	26	9	53	0	99	0	100
	2	0	95	0	78	29	1	6	52	0	100 (1.7)	0	99
	3	0	93	0	94	27	17	9	36	0	99 (1.7)	0	97
	4	0	90	0	79	29	11	10	38	0	91	0	97
Sc15	1	0	97	0	98	8	27	5	46	0	99(1.7)	0	98
	2	0	99	0	97 (2.8)	9	32 (7.7)	6	39	0	94	0	97
	3	0	95	0	80	4	32	10	41	0	95	0	83
	4	0	90	0	74 (2.8)	5	19	13	24	0	95	0	74
StA15	1	0	98	0	88	12	18	11	25	0	100	0	100
	2	0	99	0	86	11	22	8	17	0	100	0	100
	3	0	80	0	70	17	14	26	18	0	98	0	97
	4	0	71	0	57	22	14	22	15	0	95	0	94
Average		0	96	0	91	12	43	8	50	0	99	0	97

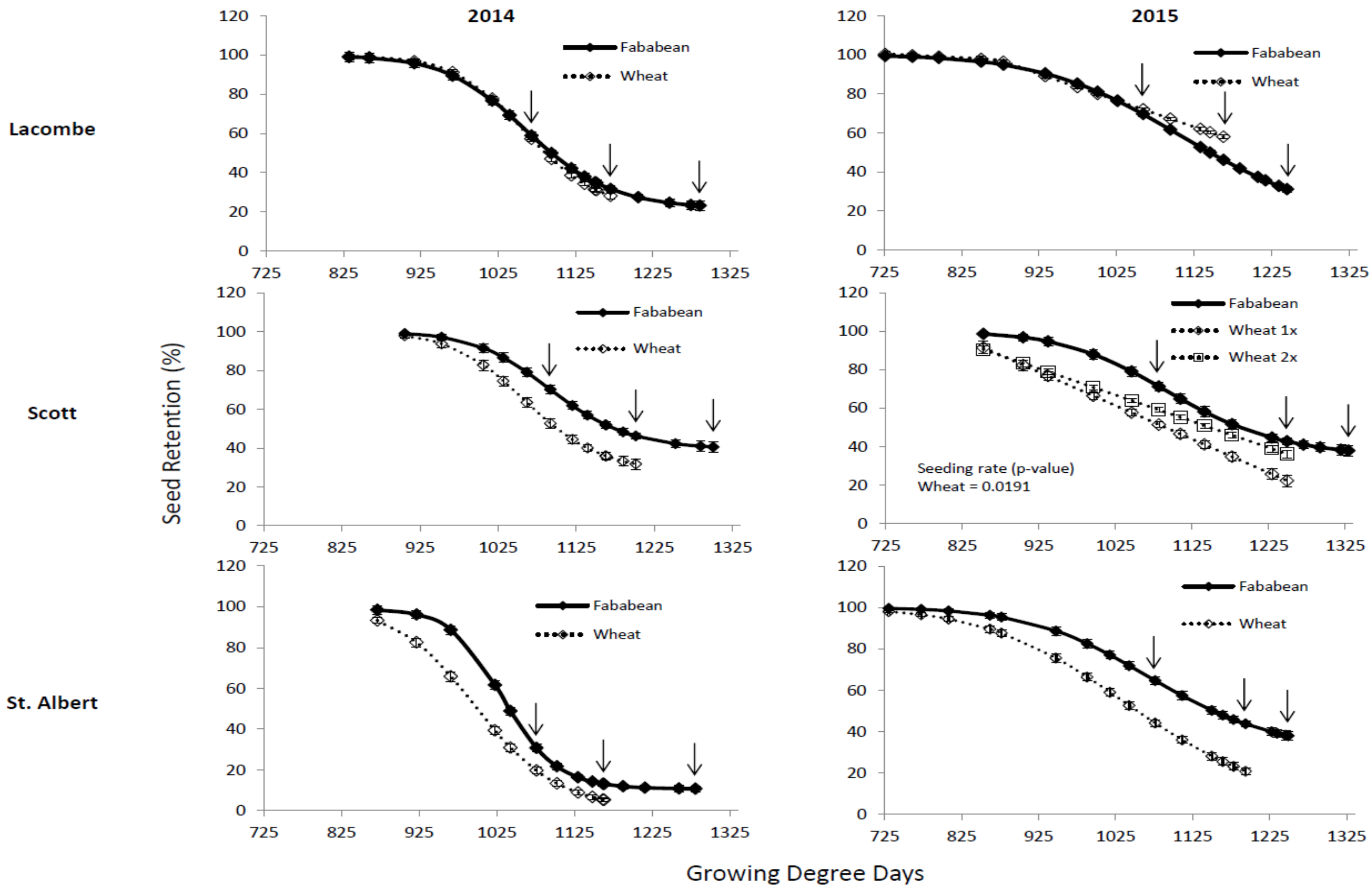

Figure 3-1. Wild oat seed retention as a function of growing degree days (GDD) and treatment by site-year. Regression equation parameter estimates are listed in Table A-1. Arrows indicate wheat swath timing, wheat direct-harvest timing and fababean direct-harvest time, respectively, from left to right. SE bars and p-values for seeding rate coefficient comparisons are shown.

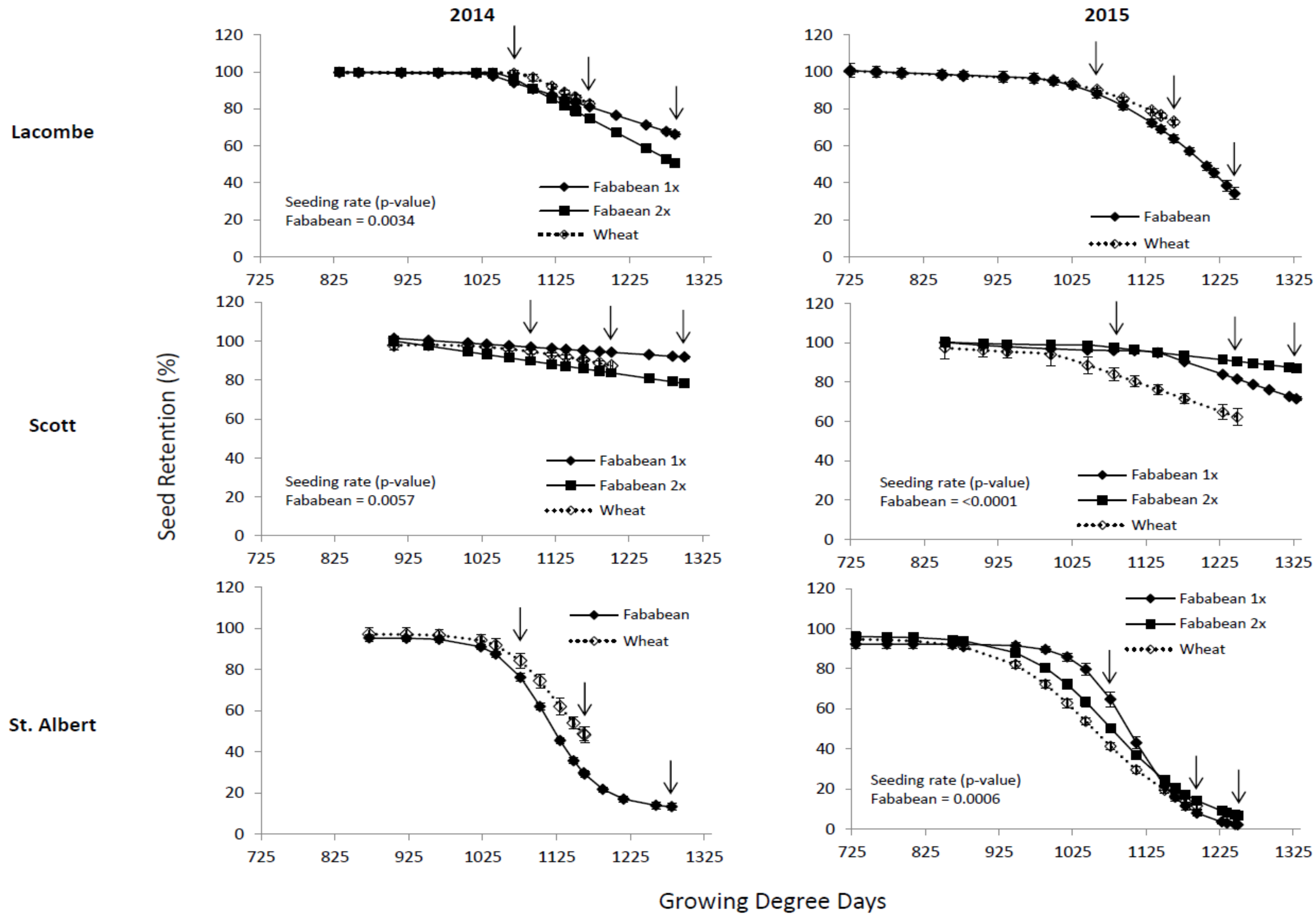

Figure 3-2. Cleavers seed retention as a function of GDD and treatment across site-years. Regression equation parameter estimates are listed in Table A-2. Arrows indicate wheat swath timing, wheat direct-harvest timing and fababean direct-harvest time, respectively, from left to right. SE bars and p-values for seeding rate coefficient comparisons are shown.

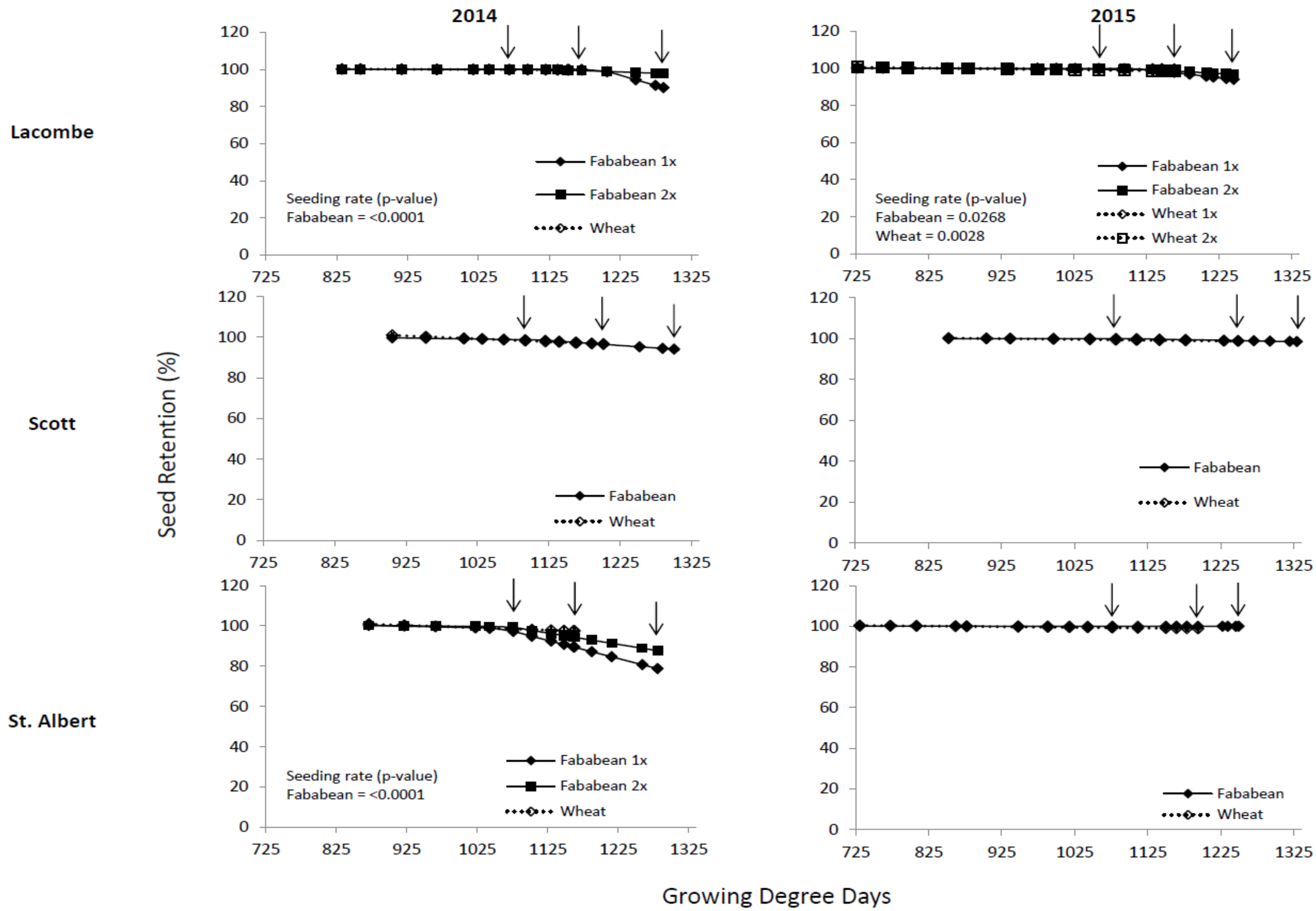

Figure 3-3. Canola seed retention as a function of GDD and treatment across site-years. Regression equation parameter estimates are listed in Table A-3. Arrows indicate wheat swath timing, wheat direct-harvest timing and fababean direct-harvest time, respectively, from left to right. SE bars and p-values for seeding rate coefficient comparisons are shown.

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Chapter Four: Identifying Critical Control Points in the Wild Oat (*Avena fatua*) Life Cycle, and the Potential Effects of Harvest Weed Seed Control[2]

4.1 Introduction

Herbicide resistant weeds occur on an estimated 37% of agricultural land in western Canada (Beckie et al. 2013a). Wild oat, an annual grass, is the most common herbicide resistant weed species, present on 44% of surveyed fields (Beckie et al. 2013a) in the Prairies. Wild oat is a species of particular concern as an estimated $500 million dollars are spent on control each year in western Canada (Beckie et al. 2012). In addition, it is the second most abundant weed in the Canadian Prairies (Leeson et al. 2005). It is a spring annual species that typically emerges between April 15 and May 15 on the Northern Great Plains (Beckie et al. 2012). However, wild oat has secondary cohorts that emerge throughout the growing season (Beckie et al. 2012). Under competitive environments, wild oat will typically produce between 20 and 70 seeds, but has produced over 150 seeds per plant (Beckie et al. 2012). Wild oat seed shatters as it matures; an estimated 80% of wild oat seed is lost prior to wheat harvest (Shirtliffe et al. 2000). Wild oat has primary and secondary seed dormancy (Beckie et al. 2012) allowing it to survive in a seed bank typically 4 to 5 years (Van Acker 2009). In addition, wild oat has exhibited resistance to ACCase and ALS inhibitors as well as triallate and difenzoquat, significantly limiting available herbicide options for control (Beckie et al. 2012). Wild oat is also the weed with highest risk of evolution of glyphosate resistance in western Canada (Beckie et al. 2013b). Development of non-herbicidal control methods is needed to ensure timely delivery of alternate control measures to producers.

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Integrated weed management (IWM) practices including diverse crop rotations, increasing seeding rates, as well as using competitive crops and cultivars applied consistently over several years can suppress wild oat populations (Harker et al. 2009). At 25% herbicide rates, combined IWM techniques have suppressed wild oat densities, biomass and seed production but were not sufficient to stop populations from increasing over time (Harker et al. 2009). In Australia, where herbicide resistant weeds pose a significant problem for crop production, innovation has led to a number of diverse practices being developed under the Harvest Weed Seed Control (HWSC) paradigm (Walsh et al. 2013) including narrow windrow burning, chaff carts, bale-direct systems, chaff lines, chaff decks and the Harrington Seed Destructor. HWSC targets weed seeds after production but prior to entry in to the weed seed bank. In this case seed production is not limited, but the dispersal and survival of the newly produced seed is targeted. This method has proven effective for annual ryegrass and wild radish, two of the most problematic weeds in Australia (Walsh et al. 2013). HWSC has been successfully adopted in Western Australia, however, adoption elsewhere is limited. HWSC provides a potential new opportunity for targeting wild oat. However, for HWSC to be effective weed seeds must be retained on the plant at crop harvest (Walsh and Powles 2014), at a height from which they can be collected, and decreased survival of newly shed seed must have a substantial impact on overall population growth rate (λ). Optimally, HWSC would cause population decline, alone or in combination with other IWM control measures. It is not yet clear which combination of IWM techniques and HWSC methods will be the most effective. While field testing is necessary to determine combination efficacies, modelling may also provide an efficient and effective tool for identifying weed vulnerabilities and predicting the impacts of HWSC and IWM methods on population growth.

Demographic modeling provides several analytical tools that allow estimation and comparison of the population growth rate of a species under different management treatments and examination of how the growth rate relates to vital rates such as survival and fecundity (Caswell 2001). It has been used to investigate the impact of different agronomic treatments on weed population growth rates (Davis and Liebman 2003; Davis et al. 2003; Davis et al. 2004). Demographic models may be analyzed to ask 'what if?' questions (i.e., what would happen to population growth rate X if parameter Y is changed by management?). These types of questions are answered by prospective and retrospective perturbation analyses. Prospective analysis identifies the vital rates or parameters that most highly impact the population growth rate (Caswell 2000, 2001). In demographic models this is called sensitivity or elasticity. Sensitivity is the absolute change in population growth as a result of a small, absolute change in a vital rate while elasticity is the relative change in population growth as a result of a relative change in a vital rate, both while keeping the other vital rates constant (Caswell 2000, 2001). Elasticity is bound below +1; an elasticity of 1 indicates direct proportional changes; a 10% change in a vital rate results in a 10% change in λ, while an elasticity of 0.5 indicates that a 10% change in a vital rate results in a 5% change in λ. Vital rates with larger elasticities make better management targets, as changes will have proportionally more impact on the overall population growth rate. However, in many cases if λ is highly elastic to a specific vital rate, the vital rate often has limited variance or is difficult to control; in many cases high elasticity values are associated with those parameters that are highly evolutionarily conserved (de Kroon et al. 2000). Additionally, the changes in elasticities that result from a change in one of the vital rate values can be examined while other vital rates are held constant. Retrospective analysis in the form of a Life Table Response Experiment (LTRE) allows treatments to be contrasted, and variation or lack thereof in population growth rates to be attributed to variation in the vital rates (Caswell 2001). They allow for the comparison and contrast of the treatments in terms of which parameters are contributing to the difference observed in population growth rates. Finally the model can be used to determine the value of a vital rate (i.e., survival) that would complete the model for a target growth rate when all other parameters are held constant (i.e., for $\lambda = 0.5$, $s_{new} = x$). These analyses combined can allow determination of the most efficient target control rate of HWSC, and thresholds where additional IWM techniques are required. They also allow an understanding of how the different treatments cause variation in the vital rates and the population growth rates.

The objective of this paper is to identify points in the wild oat life cycle that are valuable to development of integrated weed management plans as changes in those parameters highly impact the overall population growth rate. To identify those points, the elasticity of wild oat population growth rates to changes in vital rates under different management regimes using demographic data from field trials previously described by Harker et al. (2009) and Polziehn (2011), as well as wild oat biology literature, will be determined. The effect of weed management techniques like HWSC on wild oat populations will be inferred from elasticity analysis. Vital rates that are impactful to the population growth rate will be identified as potential control points. LTRE analysis will identify variation in wild oat vital rates in response to different agronomic treatments. Finally the efficacy of HWSC methods required to achieve a target population growth rate will be modeled.

4.2. Materials and Methods

Demographic data including seedling emergence, seedling mortality, fecundity, and estimated seed bank density of wild oat was collected in trials designed to test the impacts of integrated weed management techniques on wild oat populations over time. Site establishments, methods and results were described in Harker et al. (2009) for 2001 to 2005 and by Polziehn (2011) from 2006 to 2007. As described by Polziehn (2011), seed banks were estimated through 10 soil cores to 5 cm depth in an extended 'W' pattern per plot, and bulked for each plot with collected chaff. Seed bank densities were determined prior to seeding in each year. Bulked soil core samples were mechanically and hand cleaned and three sub-samples from each plot were germinated. Seeds that did not germinate were subjected to tetrazolium testing to determine viability. Wild oat was established at low levels in plots seeded to either continuous barley or a barley-pea-barley-canola rotation. Barley cultivars were either short or tall, and seeded at either 200 seeds m^{-2} (1x) or 400 seeds m^{-2} (2x). In addition, herbicides in all crops were either applied at the recommended rate (1x), half the recommended rate (0.5x) or a quarter of the recommended rate (0.25x). While trials were conducted at three locations (Lacombe, Beaverlodge and Fort Vermillion, AB), only detailed data from the Lacombe site was used to parameterize the demographic models. In addition, only specific treatment combinations are considered: short barley-1x seeding rate-continuous barley at 0.25x (treatment 1) and full herbicide rates (treatment 3), and tall barley-2x seeding rate- rotation at 0.25x (treatment 22) and full herbicide rates (treatment 24) (Table 4-1). These treatments represent the extremes in the agronomic weed management treatments considered in the field study, both with and without the presence of simulated herbicide resistance using the 0.25x herbicide rate. They are the treatments most likely to show differences in population growth rate, elasticities and LTRE's based on different management impacts. In addition, these treatments depict potential population growth rate responses upon the evolution of herbicide resistance both with and without IWM techniques implemented. Rotational treatments consider wild oat demographics in canola in 2006 and in barley in 2007. Models were limited to Lacombe data in 2006 and 2007 as this is where and when the most detailed data was collected, leading to the fewest necessary assumptions.

4.2.1 Parameterization of the Model and Population Growth Rates.

A periodic matrix model was used to describe population growth rate (λ) of wild oat, similar to that described by Davis (2006) for annual weeds (Equation 4-1) (Caswell 2001). Model parameters include s_w (proportion of individuals surviving the overwinter seed bank), g (proportion of seed recruited from the seed bank), s_{sdl} (proportion of seedlings surviving to maturity), f (average fecundity per plant), s_{new} (proportion of newly shed seeds surviving), and s_s (proportion of seeds that survive the seed bank over the growing season).

$$\lambda = s_w \times g \times s_{sdl} \times f \times s_{new} + s_w \times s_s \times (1 - g) \quad [4\text{-}1]$$

The two components of the equation describe the above- and below-ground pathways of annual plants like wild oat, respectively. To follow the above-ground pathway, a wild oat seed in the seed bank must survive the winter (s_w), emerge (g), survive to maturity (s_{sdl}), produce seed (f) and enter the seed bank (s_{new}). To survive the below-ground pathway a wild oat seed must enter the seed bank and survive the winter (s_w), survive the growing season in the seed bank (s_s), and not be recruited within the year (1-g). Survival of seeds in the seed bank over winter (s_w) occurs on both the above- and below-ground pathway and is the only parameter on both pathways. Both pathways consider the proportion of individuals surviving each pathway as well as the production of new individuals from the above ground pathway. In relation to agronomic practices, s_{sdl} would be targeted by in-crop herbicides, both s_{sdl} and f targeted by crop competition, and s_{new} would be the target of HWSC methods. Seed loss prior to harvest, seed removal in grain, fatal germination and seed predation prior to winter would also influence s_{new}.

Parameters including fecundity (*f*), proportion of seed recruited (*g*), and proportion of seedling survival (s_{sdl}) were parameterized using data from Harker et al. (2009) and Polziehn (2011) for each treatment and replicate. The parameter *g* was calculated based on measured seed bank densities multiplied by estimated seed survival over winter compared to observed seedling emergence. Proportional overwinter seed survival (s_w), and proportions of seed surviving over the growing season (s_s) were estimated from the literature (Martin and Felton 1993; Zorner et al. 1984) combined with biological knowledge of wild oat (Beckie et al. 2012). Proportional seed survival in the seed bank over both summer and winter were estimated at 0.9 based on the literature (Martin and Felton 1993; Zorner et al. 1984). Data for proportion of newly shed seed surviving (s_{new}) was least available and was assumed to equal 1.0 in initial models. Use of literature values and estimates was done understanding that parameters to which λ is highly elastic require more accurate measurements for model reliability.

Population growth rates were analyzed using a mixed model ANOVA in SAS 9.3 (SAS Institute 2010) where treatment and year were fixed effects and replicate nested in year was a random effect. LSmeans were obtained and a pdiff statement used to obtain all comparisons of population growth rates between treatments using a Bonferroni corrected $\alpha = 0.0056$ (=0.05/9 comparisons) to account for Type 1 error in the 9 comparisons of interest. Comparisons included within each treatment between years, and between treatments within each year.

4.2.2. Elasticity of Population Growth Rate to the Parameters.

Elasticity analysis was used to quantify the proportional change in λ resulting from a proportional change in vital rates (Caswell 2001). Elasticities were calculated using Equation 4-

2 (Caswell 2001), where E_{ij} is the elasticity of λ to a proportional change in the parameter a_{ij}. If, for example, E_{ij}= 0.5, a 10% change in a_{ij} leads to a resulting 5% change in λ.

$$E_{ij} = \frac{a_{ij}}{\lambda}\frac{\partial \lambda}{\partial a_{ij}} \qquad [4\text{-}2]$$

Elasticities were compared amongst treatments to identify treatment effects using Proc GLIMMIX in SAS with a Beta error distribution to account for the continuous proportion nature of the elasticities. For the ANOVA, treatment and year were fixed effects and replicate nested in year was a random effect. LSmean estimates and standard errors were obtained with an iLink function to obtain means by year and treatment on the original data scale.

Elasticity analysis was also conducted for each parameter when the model was evaluated over a range of s_{new} from 0 to 1 in 0.1 intervals with all other parameters held constant for treatments 1 and 3. This allows for observations of trade-offs in elasticity and identification of reduced survival where further reductions in s_{new} are no longer the most efficient management techniques to target.

4.2.3. Life Table Response Experiment.

A retrospective analysis was completed using the methodology described by Caswell (2001) through a Life Table Response Experiment. Life Table Response Experiment (LTRE) analyses decompose variation observed in population growth rates into contributions from differences in vital rates that determine λ. Treatments were only compared within year and the reference matrix was always treatment 1 (Short-continuous barley- 1x seeding rate- 0.25x herbicide). A data frame of all possible replicate combinations within treatment comparisons was created. Rows in each data frame were resampled with replacement in R (R version 3.1.2, R Core Team 2014) in order to create a bootstrap sample of 2000 according to Caswell (2001). For each row in the bootstrap sample sensitivities, differences and contributions were calculated and the contribution column was sorted in numerically decreasing order. The 95% confidence intervals for contribution were then acquired by selecting the 50th and 1950th values from the sorted contribution column and the median of the contributions identified.

4.2.4. Required Control of s_{new} to Decrease λ.

To evaluate the proportion of newly shed seed survival that would cause wild oat populations to decrease, the periodic matrix model equation was rearranged to:

$$s_{new} = \frac{\lambda - [s_w * s_s * (1-g)]}{(s_w * g * s_{sdl} * f)} \qquad [4\text{-}3]$$

By solving the equation for a defined λ, the s_{new} required could be determined. The minimum population growth rate achievable for each treatment is estimated by only changing s_{new} for target λ = 1, 0.99, 0.9, 0.8, 0.7, 0.6, 0.5, 0.4, 0.3, 0.2, 0.1 and 0. This allows identification of treatment differences, as well as general inferences about the potential effects of HWSC methods on wild oat λ.

4.3. Results and Discussion

4.3.1. Parameterization and Population Growth Rates.

Parameterization of the population model was invalid for the tall barley-2x seeding rate rotation at the full herbicide rate (treatment 24), likely due to an underestimation of the viable seed bank. While soil cores followed by germination are a standard way of measuring weed seed banks, it is possible that cores were taken in low density areas of the plot, or that viability was underestimated during tetrazolium testing. Since fewer viable seeds were recorded in the seed bank than seedlings, the demographic model is not valid. Estimates of the viable seed bank from sampling soil and germinating the soil cores tend to underestimate the viable seeds (Fenner and Thompson 2005). The loss of the most effective weed control treatment limited the range of population growth rates between management regimes. With very few seeds recorded in the seed bank for this treatment, more plants were emerging than recorded in the seed bank, leading to invalid values for recruitment. This is due to variability and lack of accuracy in measuring the seed bank of weed species.

For all treatments with valid models λ was > 1, meaning all populations were increasing (Table 4-2). The slowest growing population was in treatment 3 (short-continuous barley-1x seeding rate-1x herbicide) in 2007 (λ=1.37). The fastest growing populations were treatment 22 (tall-rotation-2x seeding rate-0.25x herbicide) in 2007 (λ= 4.75) and treatment 3 (short-continuous barley-1x seeding rate-1x herbicide) (λ= 4.85) in 2006. In 2006 treatment 3 had a high λ despite receiving a full herbicide rate, suggesting an ineffective herbicide application, secondary emergence of wild oat, or herbicide resistant wild oat. Considering treatment 3 in 2007 (slowest population growth) and treatment 22 in 2007 (fastest population growth), there is unsurprisingly an indication that the lack of herbicide application in treatment 22 allows much higher population growth rate. If the 0.25x herbicide rate is considered to simulate herbicide resistance, it suggests the potential increase in population growth rate with the development of resistance. However, the treatment with the least amount of weed control, was not the treatment with the highest population growth rate; this may indicate some inaccuracies in the assumptions of model parameters that were not measurable.

In the ANOVA, year and treatment were non-significant effects on population growth, although there was a significant year by treatment interaction. Based on LSmeans and pdiff comparisons, two comparisons showed significant differences in population growth compared to a p-value of 0.05, but were not significantly different compared to the adjusted p-value. Those comparisons were treatment 3 compared between 2006 and 2007 (p-value = 0.02), and treatment 3 and treatment 22 in 2007 (p-value = 0.01). While the first comparison could be attributed to environmental differences between years or a less effective herbicide application, the difference between treatment 3 with herbicide and treatment 22 with a 0.25x herbicide rate may be attributable to the management regimes. However, none of the treatments in either year caused a population growth rate less than one, indicating that none of the management regimes were effective enough to cause a decline in the population. While this may be due to inaccuracies in parameter assumptions, additional management techniques are needed, particularly in the face of increasing herbicide resistance. While cropping systems in western Canada have succeeded in managing wild oat populations generally, wild oat remains a significant problem for producers; if our methods were successful in causing population decline each year, it could be expected that by this time wild oat would no longer be a problem. Further advances in wild oat control are still needed.

4.3.2. Elasticity of Population Growth Rate to the Parameters.

Elasticity of λ to proportional overwinter seed bank survival (E_{sw}) was equal to one (Davis 2006) (Table 4-2); a proportional change in the survival rate results in the same proportional change in λ. As there is no variance in the E_{sw} values (elasticity always equals 1) there was no treatment or year effect. In the single stage periodic model for annual plants, all individuals must transition through and survive the seed bank to remain part of the population. If seeds remain dormant or germinate into seedlings they must have survived over the winter in the seed bank. Therefore, the overwinter seed bank is a part of both the above- and below-ground pathways (Davis 2006). It is a ‘choke-point’ in the life cycle of annual species and is an effective vital rate to target with weed management as it has the greatest impact on population growth rate (Davis 2006). However, s_w is also very difficult to target with current management techniques. In western Canada, over-wintering seeds are difficult to target with chemicals and are protected from fatal germination and insect predation by freezing temperatures and snow-cover. Therefore, looking at the next most impactful parameters may be critical to developing an effective and ecologically-sound management regime.

Across all treatments three parameters had equal elasticities (Davis 2006) that were highest after the elasticity of lambda to s_w: fecundity (f), proportion of seedlings surviving to maturity (s_{sdl}) and proportion of newly shed seed surviving (s_{new}) (Table 4-2). There were no significant year, treatment, or year by treatment effects on elasticity of λ to any of these parameters. Elasticities ranged from 0.63 to 0.86 (Table 4-2), suggesting that a 10% change in fecundity, seedling survival or newly shed seed survival results in approximately a 6 to 9% change in population growth rate.

The ability to reduce f, s_{sdl} or s_{new} could lead to significant and important changes in the population growth rate of wild oat. Fecundity could potentially be targeted by eliminating panicles prior to viable seed set through mowing or clipping (Harker et al. 2003), or by the use of chemicals which reduce seed set. While herbicides such as glyphosate may translocate to seeds and prevent viable germination the following year, their use prior to crop maturity is not feasible.

Population growth rate was similarly elastic to s_{sdl}. Where herbicides are effective and used, wild oat seedling survival is already being managed and would be difficult to decrease further. However, where herbicides fail, either due to herbicide resistance, poor efficacy or delayed emergence, a 10% increase in seedling survival (s_{sdl}) would result in a 6 to 9% increase in λ. Seedling survival can be more effectively decreased by ensuring herbicides are applied at early stages, and through the use of a residual herbicide or a second in-crop application. Prolonging the efficacy of herbicides may be critical for management of wild oat through sustained reductions in s_{sdl}.

Reduction of s_{new} appears to be the most viable management option, either through an increase in post-harvest seed predation or through HWSC options and use of Australian innovations. While λ is highly elastic to s_{new}, 0.63 to 0.86 (Table 4-2), crop maturation must occur before wild oat seed shed for the wild oat seeds to be collected and HWSC to be effective. Wild oat seed shatter prior to crop maturation (Shirtliffe et al. 2000) may be one of the key factors that make wild oat such a problematic weed. Growing early maturing crops may allow the collection of more seeds and increase the ability of HWSC to affect s_{new}. HWSC is not the only option to impact this vital rate. Seed predation may also play a crucial role in the survival of newly shed seeds. The impact of seed predation is not well quantified in terms of its effects on weed control, however, direct seeding, increasing rotational crop diversity or increasing species richness may increase the hospitability of the environment for seed predators. This is an area of potentially beneficial research.

Across all treatments, the elasticity of population growth rate to proportion of seeds recruited (*g*) was the next highest elasticity value, ranging from 0.52 to 0.76 (Table 4-2). In most cases, increasing recruitment will increase population growth rate, except for where seedling survival is very low. In that case, increasing recruitment will cause a decrease in λ as seed bank survival is critical to population survival (Davis 2006). However, decreasing recruitment for wild oat could initially result in an increase in seed bank survival due to dormancy; death of seeds from the seed bank does occur (Fenner and Thompson 2005) and may balance out the decrease in recruitment. Recruitment is a difficult vital rate to target through agronomic management. This is a key to using demographic modelling to assess potential control points; even if the population growth rate is highly elastic to a parameter, without the tools to affect that parameter, we cannot exploit that control point.

Elasticities of λ to proportion of seeds surviving in the seed bank over the growing season are the lowest elasticity values across all treatments. The elasticity ranged from 0.14 to 0.37, less than for the other parameters (Table 4-2). As a result, agronomic practices targeting this vital rate will have the least impact on wild oat population growth rate. Increasing efforts to find management practices to target this vital rate is unlikely to achieve a satisfactory outcome. Based on these initial estimates, this may be the least productive target for wild oat control.

Data were not available for the proportion of seeds that survived in the fall and entered the winter seed bank and therefore initial modeling used a value for s_{new} of 1. By re-parameterizing the model with varying s_{new} from 0 to 1 in 0.1 intervals, elasticity of parameters across the potential values of s_{new} can be evaluated (Figure 4-1). As the proportion of s_{new} changes, the relative importance of the other parameters, and the above- and below-ground pathways, also changes. For treatment 1 and 3 in both years, below $s_{new} = 0.1$ to 0.3 the elasticity of λ to s_{new} (also s_{sdl} and f) sharply decreases (Figure 4-1). At that point, the elasticity of λ to s_s increases and becomes the parameter to which λ is most highly elastic (excepting s_w which always = 1) (Figure 4-1). Therefore, reducing s_{new} further to 0.1 to 0.3 is less effective on λ than targeting the soil seed bank at any time of the year. To effectively reduce λ, 70 to 90% of newly shed seed should be removed whether by HWSC, seed predation, or harvest. After reduction of s_{new} to that point, depleting the seed bank sustaining the wild oat population becomes critical.

Achieving 100% control of newly shed wild oat seed should not be the goal, as it is not the most efficient use of resources; combined methods that target newly shed seed and the seed bank would be a more effective and efficient management scheme. Similar to seedling survival (Davis 2006), if very few or no newly shed seeds survived control, the below-ground pathway, or the seed bank, is allowing the population to persist; as management efficacy targeting s_{new} increases, the importance of developing methods to target the seed bank also increases.

4.3.3. Life Table Response Experiment.

Life Table Response Experiment (LTRE) analyses decompose treatment effects on λ into contributions from vital rates. All treatments were compared to treatment 1, a low management, low herbicide treatment. Treatment 3, which lacked integrated weed management practices but had a 1X herbicide rate, consistently had lower fecundity and higher proportional recruitment of seeds from the seed bank (Figure 4-2 A and B). In 2006, when λ was higher than treatment 1 (4.82 vs 3.38), proportional seedling survival was also significantly higher confirming that herbicide control failed or a second cohort of seedlings emerged (Figure 4-2 A). In 2007, when λ was lower than treatment 1 (1.37 vs 3.57), proportional seedling survival is also lower, suggesting herbicide treatment was successful, a more typical result of herbicide application (Figure 4-2 B).

Comparing treatment 22 (IWM, low herbicide) with treatment 1 (no IWM, low herbicide), λ was lower than treatment 1 in 2006 when a canola crop was grown (2.73 vs 3.38) but higher in 2007 when a barley crop was grown (4.75 vs 3.57). Treatment 22 showed consistently lower fecundity, presumably due to higher crop competition, particularly in 2006 in a competitive canola crop, but higher recruitment (Figure 2 C and D). The seed bank was larger in treatment 1 (data not shown) and available safe-sites may have limited the proportion of the seed bank that germinated (Figure 2 C and D). Proportional seedling survival in treatment 22 was lower than treatment 1 in 2006 and marginally higher in 2007, suggesting differences in herbicide effectiveness in canola and barley crops. It should be noted that variation in seedling survival contributed the least to the variation in population growth rate across all treatment comparisons.

Stochasticity of wild oat seedling survival, recruitment and fecundity demonstrates the ability of wild oat populations to exploit a gap in management. A single release from control allows for a transient increase in λ (Table 4-1, Figure 4-2A) and subsequent weed problems. Using multiple methods of controlling weeds may decrease the risk of an exploitable management gap.

4.3.4. Required Control of s_{new} to Decrease λ.

Use of Equation 4-3 allows for the value of s_{new} to be determined to achieve a specific population growth rate, assuming other parameters are unchanged. For a stable population ($\lambda=1$), the minimum proportion of newly shed seed surviving ranged between 0.15 and 0.32 depending on treatment (Figure 4-3). Averaged across treatments, a stable population requires an s_{new} reduced to just over 0.2. This means that if survival of newly shed seed is reduced by 80%, the population will only be maintained and not declining. For the population to decline by half, s_{new} must be equal to 0 for most treatments, but 0.04 and 0.12 for treatment 22-2006 and treatment 3-2007 respectively. Reductions to this level may be difficult to obtain, and as discussed above for the elasticity analysis, may not be the most efficient or feasible target. HWSC combined with techniques that target the seed bank may be the most feasible management combination moving forward to successfully reduce wild out populations. The survival of seeds after harvest and prior to winter has been poorly quantified in western Canada.

Quantification of s_{new} will allow for a more accurate model, and more accurate suggestions regarding management options.

Although wild oat seed retention in in Australia looks promising for HWSC (Walsh and Powles 2014), Canadian estimates (Shirtliffe et al. 2000; Chapter 3) suggest high seed losses prior to crop maturity. If too many wild oat seeds are shed prior to crop harvest, the effectiveness of the Harrington Seed Destructor or other HWSC may be reduced. It may be possible, with shorter season crops, to increase the proportion of seeds available for control by HWSC methods. Increasing this proportion may be vital to successful control of wild oat in the future.

Demographic modeling has provided an initial understanding of the trade-offs between vital rates resulting in different population growth rates (λ) under different management regimes. This model compared the impact of management intervention opportunities on population growth rates and also showed the stochasticity of population growth under the same treatment between years. It suggests that in the absence of seedling control, herbicide resistant wild oat populations will increase rapidly. This was demonstrated by the comparison of treatments 3 in 2006 and 2007. This model also suggests that over-winter seed bank survival, survival of newly shed seed, seedling survival and fecundity are the parameters with the highest impact on population growth rate. Of these parameters seed bank survival and newly shed seed survival provide good potential targets for innovative technologies. Modeling facilitates the assessment of control levels required by HWSC to effectively decrease the population growth rate, and a benchmark for control levels that maximize efficiency and impact. However, quantification of several critical parameters is needed to increase modeling accuracy and predictability. Population growth rate is highly elastic to survival of the over-winter seed bank, however, measures of this vital rate are difficult to obtain experimentally. This model is applicable to wild oat populations near Lacombe, Alberta, considered in two years; for a more broadly applicable model, data from other locations and years is required, although data can be time- and labour-intensive to obtain. This model suggests that HWSC will have limited impact on wild oat populations unless combined with other IWM techniques. Early seed loss of wild oat limits the seed available to target with HWSC, increasing the difficulty of causing population decrease with HWSC methods alone. Wild oat seed shatter has been and remains an effective way to avoid seed removal at harvest. In combination with seed dormancy that allows populations to survive periods where the above ground pathway is limited, an ability to evolve herbicide resistance and an ability to exploit lack of control with rapid increases in population growth rate, wild oat remains a difficult weed to control. While early season crops may provide a potential opportunity to increase HWSC efficacy, other methods may need to be developed to effectively manage wild oat, particularly as herbicide resistance continues to increase.

Table 4-1. List of treatments used to parameterize the matrix model from trials described in Harker et al. (2009) and Polziehn (2011).

Treatment #	Rotation	Year 2006	Year 2007	Type of Barley	Seeding Rate	Herbicide Rate
					---sds m^{-2}---	
1	Continuous Barley	Barley	Barley	Short	200	0.25x
3	Continuous Barley	Barley	Barley	Short	200	1x
22	Diverse	Canola	Barley	Tall barley	400	0.25x
24	Diverse	Canola	Barley	Tall barley	400	1x

Table 4-2. Population growth rate (λ) and elasticity of the population growth rate to each parameter and treatment, as calculated using Equation 4-1.

Treatment	Year	λ*	E_{sw}	E_{snew}, E_f, E_{ssdl}	E_g	E_{ss}
1	2006	3.38 (±0.91)	1	0.82 (±0.10)	0.76 (±0.10)	0.18 (±0.10)
	2007	3.57 (±0.91)	1	0.86 (±0.09)	0.77 (±0.10)	0.14 (±0.09)
3	2006	4.85 (±0.91)	1	0.86 (±0.09)	0.77 (±0.10)	0.14 (±0.09)
	2007	1.37 (±1.02)	1	0.63 (±0.16)	0.58 (±0.16)	0.37 (±0.16)
22	2006	2.73 (±1.02)	1	0.64 (±0.16)	0.52 (±0.14)	0.36 (±0.16)
	2007	4.75 (±0.91)	1	0.84 (±0.09)	0.72 (±0.11)	0.16 (±0.09)

*λ= population growth rate, E_x= Elasticity of λ to parameter x, s_w = proportion of individuals surviving the overwinter seed bank, g = proportion of seed recruited from the seed bank, s_{sdl} = proportion of seedlings surviving to maturity, f = average fecundity per plant, s_{new} = proportion of newly shed seeds surviving, and s_s = proportion of seeds that survive the seed bank over the growing season.

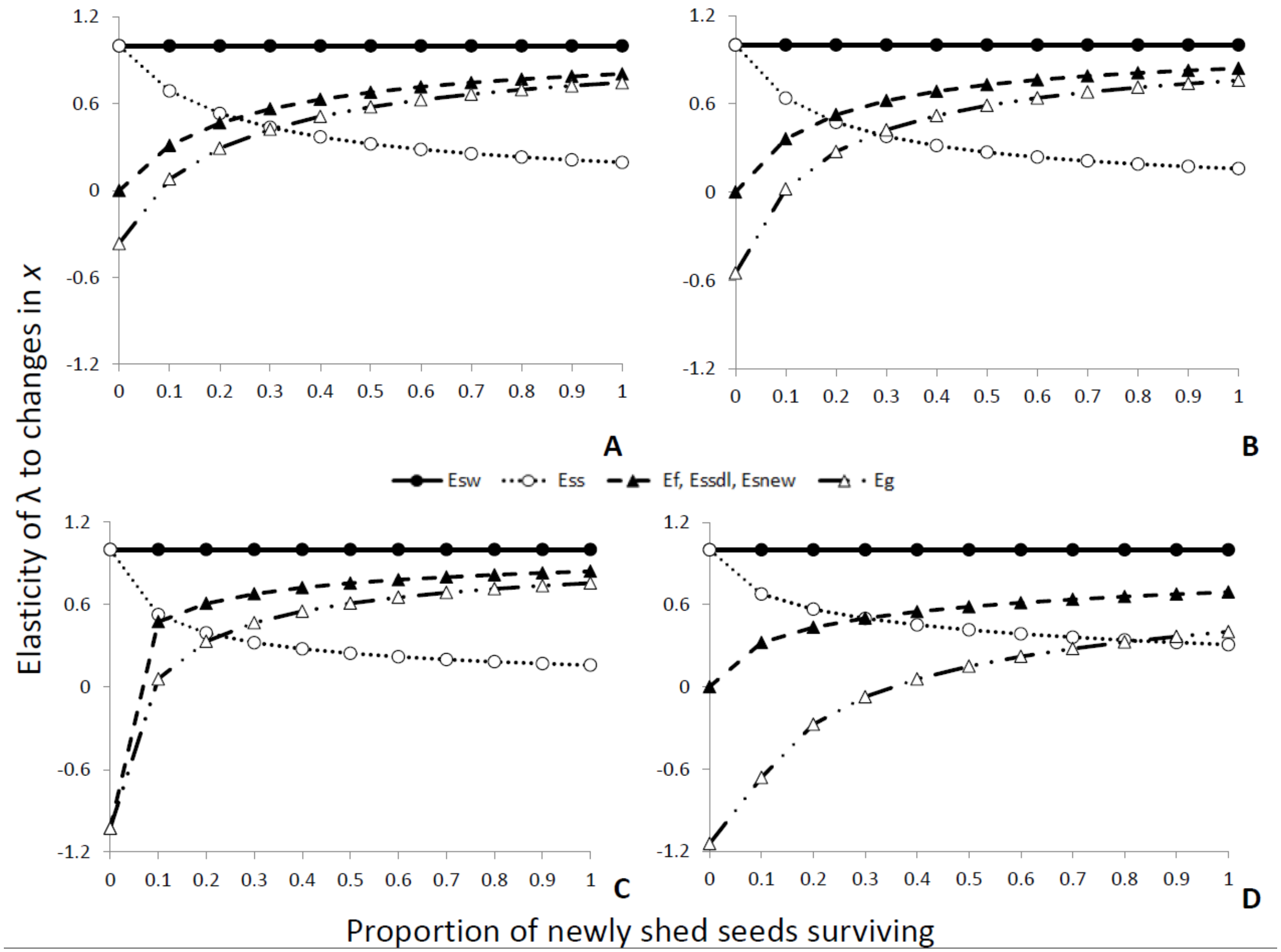

Figure 4-1. Elasticity of λ to changes in the vital rates as affected by the proportion of newly shed seeds (s_{new}) surviving from 0 to 1. A) Treatment 1, 2006. B) Treatment 1, 2007. C) Treatment 3, 2006. D) Treatment 3, 2007. E_{ij} represents the elasticity of λ to parameter *ij*. s_w = proportion of individuals surviving the overwinter seed bank, g = proportion of seed recruited from the seed bank, s_{sdl} = proportion of seedlings surviving to maturity, f = average fecundity per plant, s_{new} = proportion of newly shed seeds surviving, and s_s = proportion of seeds that survive the seed bank over the growing season.

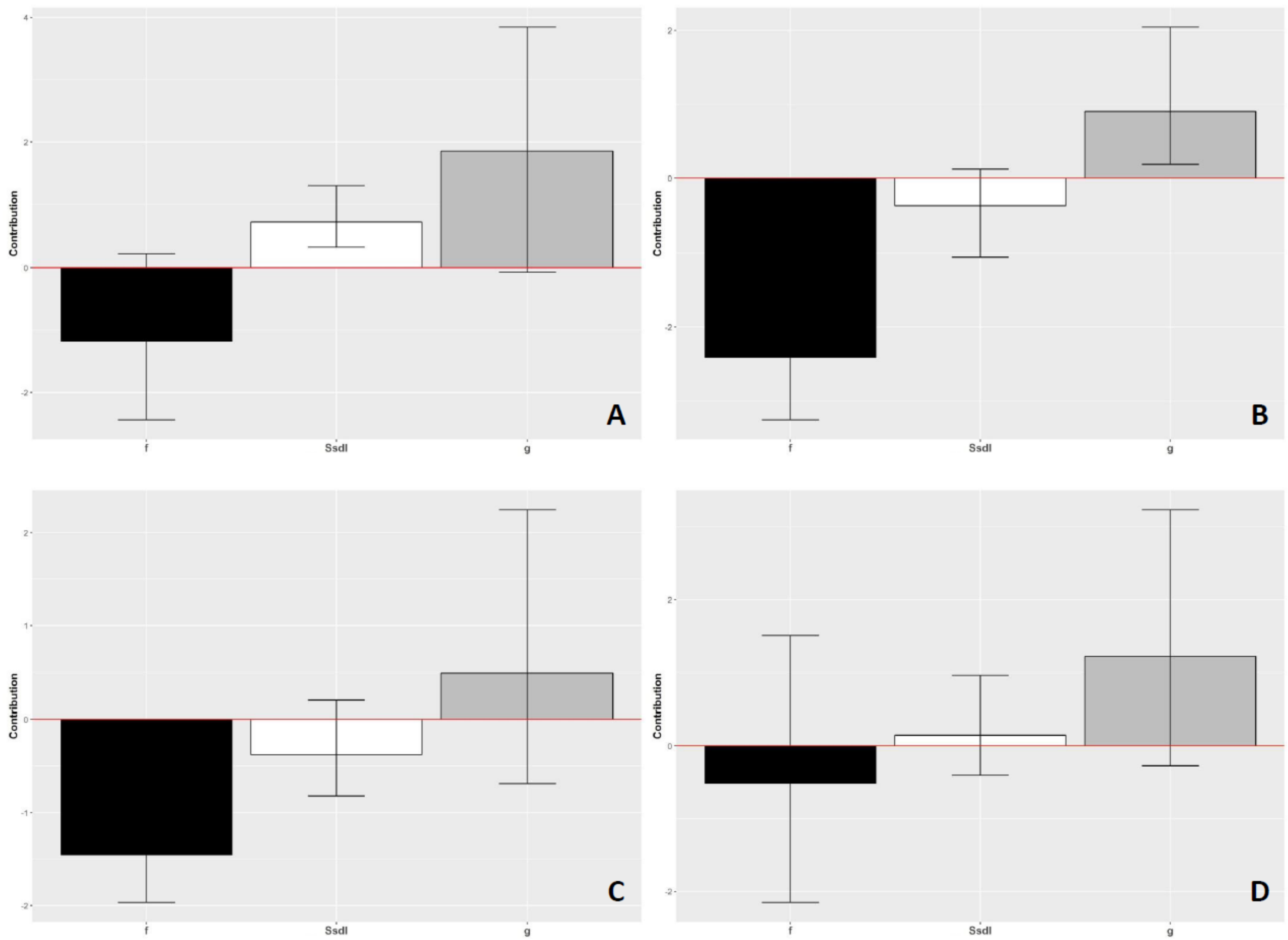

Figure 4-2. Life Table Response Experiment (LTRE) comparing A)Treatment 3 to Treatment 1 in 2006, B) Treatment 3 to Treatment 1 in 2007, C) Treatment 22 to Treatment 1 in 2006, and D) Treatment 22 to Treatment 1 in 2007. Contributions of the parameters fecundity (*f*), proportion of seedlings surviving (s_{sdl}) and proportion of seeds recruited (*g*) describe variation or similarities between the treatment population growth rates and compare the relative contributions with Treatment 1 as the reference. Vertical bars are medians of the parameter contributions and error bars are based on 95% confidence intervals from the bootstrapped contributions.

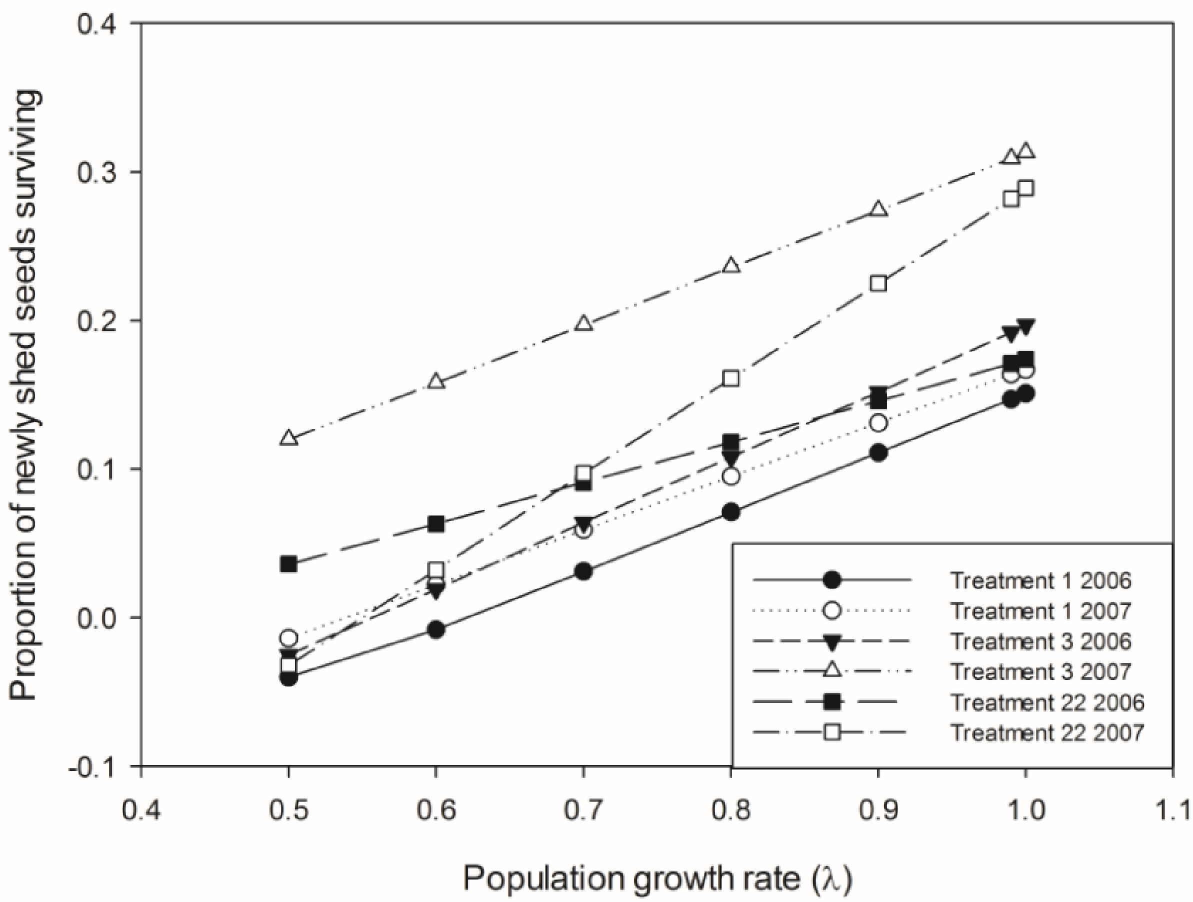

Figure 4-3. Proportion of newly shed seed (s_{new}) surviving required for the designated population growth rates, determined for each treatment using the equation $s_{new} = \frac{\lambda - [s_w * s_s * (1-g)]}{(s_w * g * s_{sdl} * f)}$ where s_w = proportion of individuals surviving the overwinter seed bank, g = proportion of seed recruited from the seed bank, s_{sdl} = proportion of seedlings surviving to maturity, f = average fecundity per plant, s_{new} = proportion of newly shed seeds surviving, s_s = proportion of seeds that survive the seed bank over the growing season and λ = population growth rate.

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Chapter Five: Factors Affecting Weed Seed Devitalization with the Harrington Seed Destructor[3]

5.1. Introduction

The evolution of weed resistance to herbicides (Heap 2017), and a scarcity of new herbicide modes of action (Duke 2012), have pressured the agriculture industry to develop alternatives to chemical weed control. Australia has led the innovation stream with the development of harvest weed seed control (HWSC) systems. HWSC targets weed seeds that would typically be distributed by combine harvesters in the chaff residue and aims to destroy those seeds to prevent introduction into the seed bank (Walsh et al. 2013). There are a number of methods of HWSC being used including narrow windrow burning, chaff carts, direct bale systems (Walsh et al. 2013), chaff tramlining (or chaff deck) and windrow rotting (or chaff lining) (Australian Herbicide Resistance Initiative 2014, 2015). An additional HWSC technology that has received substantial attention is the Harrington Seed Destructor™ (HSD), a tow-behind machine that processes chaff through a cage mill to devitalize weed seeds (Walsh et al. 2012).

The benefits of using the HSD over other HWSC technologies is the retention of all residues across the field for nutrient cycling and moisture conservation and no additional labour required after harvest in each field (Walsh et al. 2012). Additionally, there is physical processing of the weed seed rather than relying on composting, burning or residue removal as for some other HWSC methods. However, following commercialization, adoption of the HSD has been slow due to cost and a lack of desire by producers to tow a large machine (Australian Herbicide

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Resistance Initiative 2016). In March 2016, the commercialization of the Integrated Harrington Seed Destructor™ (iHSD) was announced, a system of two mills incorporated in the back of the harvester and powered by the harvester, providing the same method of weed control without the towing requirement (de Bruin Engineering 2017). The iHSD is based on the same cage mill as the original HSD, however, rather than two spinning cages making up the mill, the iHSD has only one cage spinning but twice as fast. The cost of the iHSD is also less than that of the original unit ($160,000 AUD vs $200,000 AUD), making it a more viable system for producer use, and providing equivalent efficacy (Australian Herbicide Resistance Initiative 2016). It was determined that adoption of the HSD was most economical when herbicide-resistant weeds (particularly to non-selective herbicides) were present, when crop yields were high and the annual cropping area was a minimum of 3000 ha (Jacobs and Kingwell 2016). However, this evaluation was done with the original HSD; the lower cost of the iHSD will make it more economical in other situations. As this analysis was based on Australia cropping systems and weed species through use of the Ryegrass integrated management simulation model, the economics of adoption will likely differ in different countries and in different agro-ecoregions.

In Australia, the HSD has been >90% effective on rigid ryegrass (*Lolium rigidum* Gaud.), wild radish (*Raphanus raphanistrum* L.), wild oat (*Avena* spp.) and brome grass (*Bromus* spp.) (Walsh et al. 2012). Control was greater on the larger seeds (wild oat and brome grass – 99%), than wild radish (93%) due to its protective, hard silique (Walsh et al. 2012). Other factors have been suggested to affect weed seed control with impact implements like the HSD, such as the impact speed (RPMs), number of impacts, seed size, weed species, seed strength, seed natural defenses, moisture content and chaff type, among others (Berry et al. 2015; Walsh et al. 2012).

Understanding how crop and weed seed factors affect HSD efficacy will increase understanding of potential suitability of the HSD in new agro-ecoregions.

The objective of this study was to determine the effect of some crop and weed seed parameters on HSD efficacy to determine its potential with new weeds in new agroecoregions. Weed seed viability was used to measure HSD efficacy. The parameters included weed species, weed seed size, seed number (density) to simulate variable weed infestations or sub-optimal harvester settings, chaff load to simulate different yielding crops and chaff type for comparing efficacy between crop types.

5.2. Materials and Methods

To investigate specific factors and their effects on HSD weed seed destruction, seed and chaff samples were processed while the HSD was stationary (Figure 5-1); stationary processing through the HSD minimized variability between samples but also required collection of threshed chaff as the seed destructor is designed to process chaff and not whole plant samples. To facilitate stationary threshing, chaff was collected in the fall of 2015 during harvest of unsampled plot areas at Lacombe, Alberta, and with the assistance of a local producer who used a chaff cart in the harvest of his field pea (*Pisum sativum* L.) crop. Chaff was collected from areas with minimal weed presence. Chaff samples were stored in canvas totes to allow for air drying until use.

Volunteer canola was chosen as the primary weed species for testing the HSD. Its rapid germination, minimal dormancy and high viability made it an ideal species for these studies. Additionally, volunteer canola is an increasingly prominent weed and is often introduced from harvest losses of canola crops (Cavalieri et al. 2016). Untreated F2 canola (‘CF 46H75’ in most cases) was used to simulate volunteer canola seed. Seeds were counted using an Agriculex Inc. ESC-1 seed counter (Agriculex Inc., Guelph, ON, Canada). For most studies (see details below) 10,000 seeds were used for each sample. Additional species tested included kochia (*Kochia scoparia* L. Schrad.), green foxtail (*Setaria viridis* L. Beauv), false cleavers (*Galium spurium* L.) and wild oat (*Avena fatua* L.). These species were chosen for their range of seed size and for being common problem species in western Canada. Preliminary viability testing was conducted on multiple seed lots of all species through germination testing in 100 mm x 15 mm size Petri dishes with blue germination blotting paper (Anchor Paper Co., St. Paul, MN). Each dish received 7 mL of water and was germinated in the dark at room temperature (~22 C) for 2 wk. For each species, 50 seeds were germinated to determine viability prior to HSD processing and to select highest germinabilty seed lots (data not shown).

Processing of samples with the HSD occurred at the Prairie Agriculture Machinery Institute (PAMI) in Humboldt, Saskatchewan. For all experiments, four replications of each sample were used, and each experiment was conducted twice. Each sample consisted of 20 L of chaff, measured by filling 20 L pails with chaff and intermixing the seed samples. Using an approximate 3:1 ratio of grain to chaff production (M. Walsh, personal communication) and an average barley yield of 4,500 kg ha^{-1}, assuming 20 L of chaff weighs 1kg (M. Walsh, personal communication), the 20 L of barley chaff used in most samples would come from approximately 6.7 m^2 of land. The 10,000 canola seeds dispersed would result in a volunteer canola seed density of 1,500 seeds m^{-2}, which is slightly lower than typical harvest losses of this species (2500-6100 seeds m^{-2}) (Cavalieri et al. 2016). A lower average barley yield would change the area and seed distribution ranges. To ensure relatively homogenous samples, chaff and seed were mixed just prior to processing to ensure distribution of seeds throughout the sample and prevent settling and separation. Samples were introduced into the HSD intake (Figure 5-1) once the machine had reached full RPMs (i.e., 1450). Each sample took approximately 30 s to input into the seed destructor and the machine was allowed to run for an additional 30 s after input to ensure the entire sample was processed and expelled. To account for decreased air flow due to the HSD being separated from the harvester, compressed air was used at the intake and just prior to the sample entering the cage mill. This ensured that entire samples entered the cage mill resulting in improved accuracy and minimal contamination between samples. After processing by the cage mill, samples were expelled into a large cyclone attached to the machine, which allowed the air and extremely fine dust to escape out the top without loss of the sample. Samples were collected, labelled and returned to Lacombe to process.

Due to extreme mold growth when entire samples (all chaff and fine particles) were germinated, a cleaning process to eliminate as much of the fine dust/chaff as possible was used. Each sample was initially passed through hand-sieves (12/64" round hole) to remove larger residue components. Samples were then passed through an Almaco Air Blast Seed Cleaner (Seedburo Equipment Company, Des Plaines, IL) with very low wind to remove fine residues without losing seeds. Finally, samples were passed through a Clipper air and sieve cleaner (A.T. Ferrel Co. Inc, Bluffton, IN) twice to refine the sample to whole and partial seeds as much as possible (sieves selected were appropriate for seeds in the sample). These samples were then germinated in 16.6 x 24.1 x 4.4 cm germination boxes with blue blotting paper (Seedburo Equipment Co., Des Plaines, IL) on the bottom and white filter paper on the top to ensure moisture levels were maintained. Distilled water amounts were adjusted based on seed size; for canola seed samples 36 mL were used. For other species 36 mL was the starting point and moisture was increased in 6mL increments as required due to water uptake by the seeds.

Preliminary germinations with test samples indicated that all viable seeds were in the cleaned fractions and not in the chaff that had been screened out. On two samples there were exceptions where one viable seed was found outside the cleaned fraction; all samples were visually checked for potentially viable seeds during cleaning as a result. Samples were germinated for 2 wk in the dark at room temperature (~22 C) at which point any ungerminated seeds were subjected to a press test to determine viability (Sawma and Mohler 2002). The total number of viable seeds in the processed sample was equivalent to the number of germinated seeds and the number of seed evaluated as viable during the press test.

Five factors that may affect weed seed devitalization by the HSD were investigated. The first factor was weed seed species. Species were selected across a gradient of 1000-seed weights (TSW) to account for variations in the types of weed seeds that are problematic in western Canada (Table 5-1). We used kochia, green foxtail, false cleavers, volunteer canola and wild oat (Table 5-1). Seed lots had been collected over a number of years and stored for use in weed management trials where population establishment was required. Weed seed size was the second factor investigated and used F2 canola seed (73-75RR) that had been passed through multiple hand sieves to separate the seed into size categories. Sieves included 6 mm – round holes (R), 5.5 mm R, 5 mm R, and 4.5 mm R. This resulted in five seed sizes – the seeds that remained in each of the sieves plus those seeds that passed through the 4.5 mm R sieve (Table 5-1). The TSW was calculated for seed from each of these sieve sizes and used for data analysis (Table 5-1). Using sized canola seed minimizes differences in HSD efficacy due to different seed shape, external protrusions, etc.; the targeted difference between treatments in this experiment was seed size. Seed number was another factor investigated. Sample seed numbers ranged from 10 – 1,000,000 in logarithmic steps (Table 5-1), dispersed through the same 20-L volume of chaff. Chaff load was also investigated. Samples of 10,000 canola seeds were intermixed with chaff amounts ranging from no chaff to 160 L (eight, 20 L pails of chaff) (Table 5-1). These samples were processed within the same target time frame of 30 s resulting in a range of chaff volume processed within a unit time. Chaff type was the final factor investigated. Samples of 10,000 canola seeds were intermixed with 20 L of barley (*Hordeum vulgare* L.), canola or pea chaff, chosen for their different plant structure and the resulting variation in chaff composition (Table 5-1).

Experimental design varied by experiment. The chaff type was run as a randomized complete block design. All other experiments were non-randomized and organized to prevent contamination between samples. For example, in the chaff load experiment treatments started with zero chaff and increased to the highest amount with four replications of each treatment. This is similar to a herbicide dose response study where increasing rates of a herbicide would be applied to eliminate risk of contaminating lower rate treatments with higher rate residues. For seed number there is lower risk of contamination when one million seeds follows ten seeds compared to vice versa. There is no reason to expect differences in processing over time as the machine was run at a constant speed for each sample, therefore minimized contamination was the goal rather than randomization.

5.2.1. Statistical Analysis.

Percent viability was calculated using equation 1 for all treatments. Percent viability was then converted to percent of control by equation 2 and divided by 100 to result in proportional control.

$$\%\ viability = \frac{\#\ of\ viable\ seeds\ after\ processing}{\#\ of\ viable\ seeds\ in\ the\ sample} \times 100 \qquad [5\text{-}1]$$

$$\% \, control = 100 - \% \, viability \qquad [5\text{-}2]$$

Seed number in each percent control calculation was adjusted for the viability of the seed source at the time of final processing based on a germination box test with 100 seeds. Proc GLIMMIX in SAS 9.4 (SAS Institute 1995) with a beta error distribution was used to analyze proportional control data with trial repeat, treatment and their interaction as fixed effects and replicate as a random effect. If trial repeat and its interactions were not significant on proportion of seeds controlled, trial repeats were combined and reanalyzed. From this analysis LSmeans and standard errors were obtained and converted back to percent control for presentation. For the chaff type and weed species experiments, a pdiff statement with a Tukey adjustment was included in the GLIMMIX ANOVA for comparison of means (α=0.05). For seed size (canola), and chaff load, Proc Reg was used to perform linear (Equation 5-3) and quadratic (Equation 5-4) regressions, respectively. In the linear regression equation (Equation 5-3), *Y* is the proportion of seeds controlled, *x* is TSW, *m* is the slope of the line and *b* is the intercept.

$$Y = mx + b \qquad [5\text{-}3]$$

In the quadratic regression equation (Equation 4), *Y* is the proportion of seeds controlled, *x* is the chaff load volume, *a* and *b* are slope values, and *c* is the intercept.

$$Y = ax^2 + bx + c \qquad [5\text{-}4]$$

For the seed number experiment an exponential reciprocal model (Equation 5-5) was fitted using DeltaGraph (Red Rock Software Inc, Salt Lake City, UT)

$$Y = ae^{-\frac{b}{x}} \qquad [5\text{-}5]$$

where Y is the percentage of seeds controlled, x is the seed number, a is the asymptote and b is the slope parameter.

For all experiments with the exception of seed size (species), trial repeat was not a significant factor, and there was no significant interaction with treatment. Therefore, trials were combined for further analysis.

5.3. Results and Discussion

5.3.1. Weed species

For weed species, trial repeat was a significant factor ($p = 0.019$). However, the LSmeans for each species were not significantly different between trial repeats and therefore combined data are presented. Weed seed control by the HSD showed limited significant differences (kochia significantly different than all weeds except wild oat) and is unlikely to have high biological impact (Figure 5-2). There was not, as hypothesized, a linear increase in control with increased TSW but rather a significant quadratic regression (data not shown). The quadratic regression was not consistent with the hypothesis that increased seed mass results in more energetic impacts and increased control. It is likely that other properties of the seeds including shape, external structures, seed coat strength, etc., also affect the level of control by the HSD (Figure 5-2).

Control of the tested species ranged from 97.7% of cleavers to 99.8% control of kochia (Figure 5-2). Overall, there was a high level of control of all of the tested species, across a wide range of TSWs. Control of some species (i.e. kochia) may be artificially high. Kochia had low seed lot viability (34%) by the time of processing and germination, and the adjustment of the seed number for viable seeds may have increased the control of kochia to an artificially high level (underestimation of the number of viable seeds in the sample). We do not believe that this adjustment makes the measurement inaccurate as all species are still within a very narrow control level range. Additionally, the star-shaped hull that typically covers kochia seed was removed prior to seed counting to allow for differentiation of seeds and chaff; while this hull is fragile (Friesen et al. 2009), it could offer additional protection to the seed which may result in lower control values than those observed in this experiment.

Control of cleavers (Figure 5-2) may be slightly less than other tested species due to external protrusions on the seed; the bur-like hooks on the outside of the seed may have protected the seed embryo from damage. Other very large seeds with bur-like protrusions and hard seed coats (i.e. cocklebur) have also been reported to have slightly lower, but not significantly different, control than other tested species in the United States with the integrated Harrington Seed Destructor (Schwartz et al. 2017). This experiment highlights high levels of efficacy across a number of species with a wide range of seed sizes, structures and shapes.

5.3.2. Seed size

Size of canola seed had a significant main effect on the level of control by the HSD (ANOVA $p = 0.0004$). Control of canola increased linearly with TSW (Figure 5-3) (Regression $p <0.0001$). The linear model explained 35% of variation in control of canola based on the adjusted R^2; a limited range in control values likely contributes to this low R^2 value. While the effect of seed size is statistically significant, the biological or practical effect of seed size is limited. Overall control values ranged from 98.4 % - 98.8 % from the 2.2 g TSW to the 5.8 g TSW (Figure 5-3). This large range in canola seed size, which was visually apparent, would have a large effect on seeding rate if this was crop seed (almost a 3 fold difference in seeds m^{-2}). The limited effect on overall efficacy level is a positive result in terms of weed control. There are a number of small-seeded weeds globally and in western Canada. These results indicate that small-seeded weeds would still be controlled at high levels once introduced into the HSD. While this experiment provided the hypothesized linear relationship between seed weight and percent control, it is also consistent overall with the weed species experiment in that control remains high across a variety of seed sizes. The linear equation in this case estimates a minimal control of 98% based on seed size alone; other factors could reduce this value (i.e. seed strength/silique strength of wild radish) but the overall implication of this experiment is that seed size will not likely be a limiting factor in weed control with the HSD.

5.3.3. Seed number

Seed number had a significant effect on efficacy of the Harrington Seed Destructor (ANOVA $p < 0.0001$), and had a significant exponential reciprocal regression ($p < 0.01$) (Figure 5-4). The 1,000,000 seed treatment was only included in the first trial repeat due to the production of seed meal during the processing of those samples; other samples returned processed chaff with some processed seeds while the 1,000,000 seed samples resulted in seed meal with small amounts of chaff. The oil in the seeds resulted in meal sticking to different parts of the HSD setup, i.e. the collection cyclone, increasing the risk of contamination between samples. As a result, that treatment was eliminated from the second repeat to ensure the ability to continue with other studies without risking sample contamination. Between 100 and 1,000,000 seeds, control differed by just over a percent ranging from 97.3 – 98.5 % (Figure 5-4). The 10-seed treatment showed substantially less control than the other treatments (Figure 5-4); however, this was more likely an impact of sample size rather than poor control. With only 10 seeds, each surviving seed caused a loss of 10% control. As all other control is in the range of 98%, similar to the other studies, the lack of control in the 10-seed treatment is believed to be simply the effect of sample size. It is, however, possible that with fewer seeds there are less impacts per seed with the cage mill and other seeds or pieces of chaff, which decreased the control observed in that treatment. Overall, it appears that high seed inputs from high weed densities or an improperly set combine (high seed loss in canola for example) would be effectively controlled. In general, seed input density should not affect the ability of the HSD to control weed species. The treatments used would be approximately equivalent to 1.5 – 150,000 seeds m^{-2} (based on 20L of chaff from 6.7 m^2). The 100,000-seed treatment is approximately equivalent to 15,000 seeds m^{-2}. Extremes of the likely range for volunteer canola either through harvest losses or weed infestations were considered in this experiment and in general would be efficiently controlled by the HSD.

5.3.4. Chaff load

The goal for each chaff load sample was a 30 s input time. Across the 48 samples input, the input time ranged from 26-33 s, with the majority being input between 28 and 30 s. Considering samples were input manually, this was highly consistent between samples. A single pail (20 L) of chaff is approximately equivalent to that produced on 6.7 m^2 of land; therefore, 160 L of chaff would correspond to approximately 54 m^2 of land. While these areas are likely low compared to what a typical harvester would cover for area in 30 s, it was the highest volume that physically could be fed into the HSD based on manual inputs and set-up logistics. Chaff volume had a significant effect on HSD control ($p < 0.0001$). HSD control of canola initially improved with increasing chaff load, until 80 L of chaff (4 pails) (Figure 5-5). Between 4 and 8 pails (80 – 160 L), control declined again (Figure 5-5). Overall, control ranged between 97.9% with no chaff and 99% with 80 L of chaff (Figure 5-5). The reason for the quadratic relationship ($p <0.0001$) is unclear. Increased chaff may initially increase the number of times seeds are impacted in the cage mill due to reflection and redirection, followed by protection of seeds by the chaff after a certain volume threshold. However, the dynamics of motion within the cage mill are not known and not easily observed. Regardless, the limited variability in the control of canola across a wide range of chaff volumes indicates limited effects of crop yield on HSD efficacy; processing of chaff from high or low yielding crops should not have a large effect on the control of weed seeds that pass through the HSD. Results from this experiment also indicate that results of the other experiments in this study are likely applicable to weed control in both low and high yielding crops.

5.3.5. Chaff type

There was a significant effect of chaff type on HSD efficacy (Figure 5-6). Control of volunteer canola seeds in canola chaff was significantly less than control in barley or pea chaff (Figure 5-6). While this may be due to structural and component variation between the chaff types reducing control in the canola chaff, it is more likely due to an underlying presence of volunteer canola in the chaff in addition to the canola added for the treatment. Lower control may simply be due to the presence of additional canola seeds increasing the total number of seeds in the sample. Based on equation 5-1, if the number of viable seeds used to calculate percent viability is lower than is actually present in the sample, percent viability will be overestimated and percent control underestimated. A post-processing screening of the canola chaff determined that there was an inherent presence of canola seeds in the canola chaff which could have confounded the results for that chaff type. Regardless, while the control of canola in canola chaff was statistically decreased, there is less than 1% difference between chaff types (Figure 5-6). Demographically and biologically, the difference between 98% and 98.6% is unlikely to significantly impact overall weed population abundance. Additionally, the minimal differences among chaff types indicate that all the other experiments conducted on barley chaff in this study should be applicable to weed seeds in canola and pea chaff as well. These chaff types are highly dissimilar in terms of their structure and components due to differences in original plant structures and drying rates. Similar levels of control would likely be attained with other chaff types that are biologically and structurally related to the chaff types investigated (e.g., wheat chaff should be similar to barley).

5.3.6. Conclusions

These studies investigated the potential effects of weed species, seed size, seed number, chaff load and chaff type on HSD efficacy. Across the ranges of each of these factors, the HSD performed well, controlling around 98% of weed seeds in most cases. Ranges of control were small, and consistent between samples. The 10-seed treatment from the seed number experiment showed the lowest control level (ca. 84%) of all the studies, although this was likely a result of very small sample size. The ranges of each of these factors indicate potentially high HSD efficacy in many cropping situations in western Canada and the Great Plains. These studies confirm that, as in Australia and the United States, the HSD will be highly effective on seeds that are processed through the HSD (Walsh et al. 2012; Schwartz et al. 2017). On-farm studies beginning in 2017 in Alberta will evaluate weed control efficacy of the HSD in spring wheat (*Triticum aestivum* L.), canola and field pea, either swathed or direct-harvested (direct-combined). If efficacy is high, as suggested by the stationary evaluation results reported herein, then the limiting factor in weed control will be the degree of retention of seeds on target weed species produced at a collectible height at the time of swathing or direct-harvest (Burton et al. 2016, 2017, Tidemann et al. 2017).

Table 5-1. Treatments used in each of the five experiments to determine effects of weed species, seed size, seed number, chaff type and chaff load on Harrington Seed Destructor efficacy. 'R' indicates a round hole sieve.

Experiment	Species / Sieve-size	1000-seed weight
		-------------------g--------------------
Weed species	Kochia	0.95
	Green foxtail	1.58
	False cleavers	2.19
	Volunteer canola	3.8
	Wild oat	17.0
Seed size	< 4.5 mm R	2.2
	4.5 mm R	3.4
	5 mm R	4.2
	5.5 mm R	4.9
	6 mm R	5.8

Experiment	Treatment
Seed number	10
	100
	1,000
	10,000
	100,000
	1,000,000[a]
Chaff type	Barley
	Canola
	Pea
Chaff load (barley chaff)	0 - 0 L
	½ pail - 10 L
	1 pail - 20 L
	2 pails - 40 L
	4 pails - 80 L
	8 pails - 160 L

[a]based on a single experiment

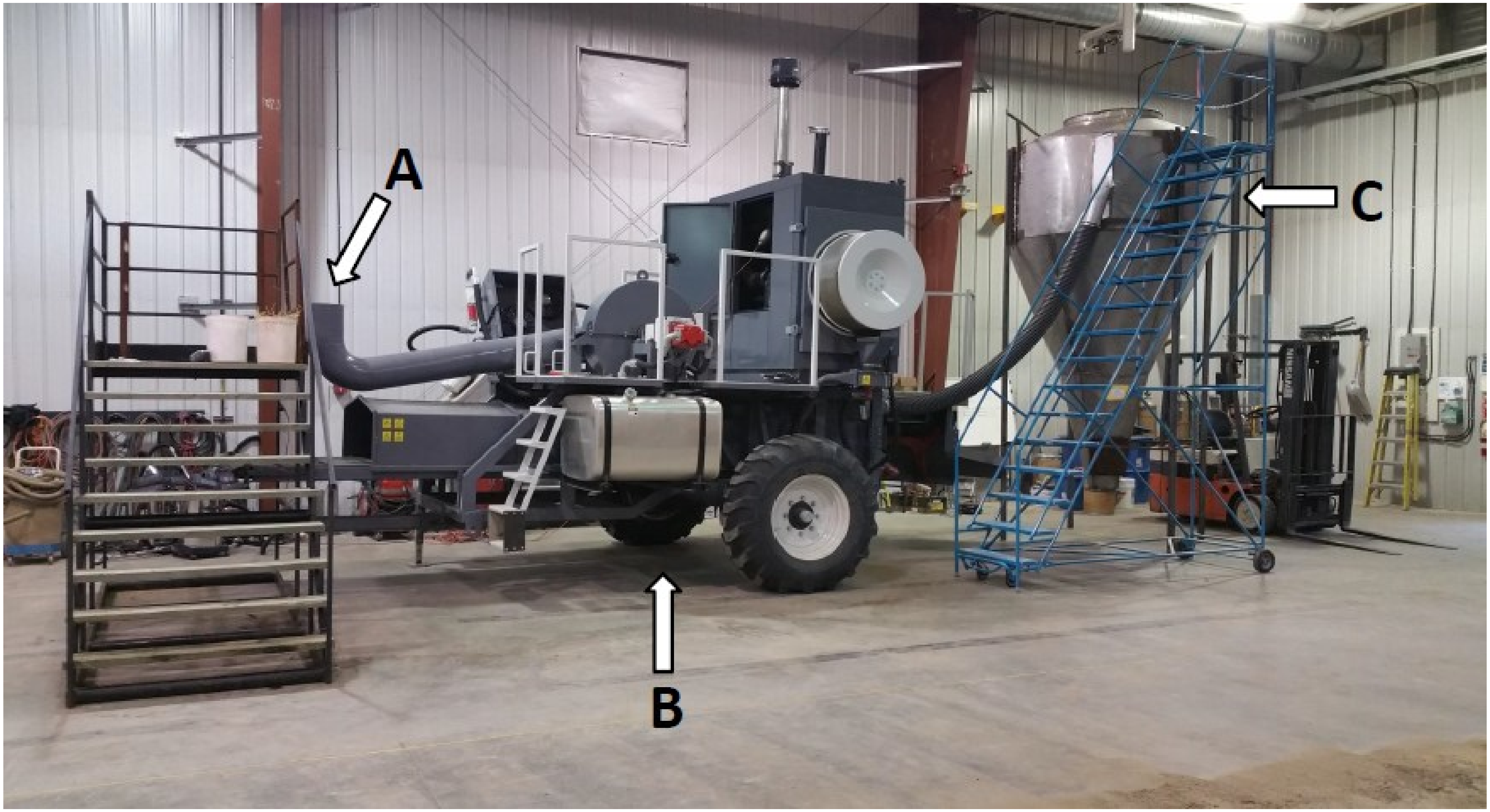

Figure 5-1. Stationary threshing set-up of the Harrington Seed Destructor. Arrows indicate (A) the intake (B) the Harrington Seed Destructor and (C) the collection cyclone. Photo credit: Josh Kirsch, PAMI.

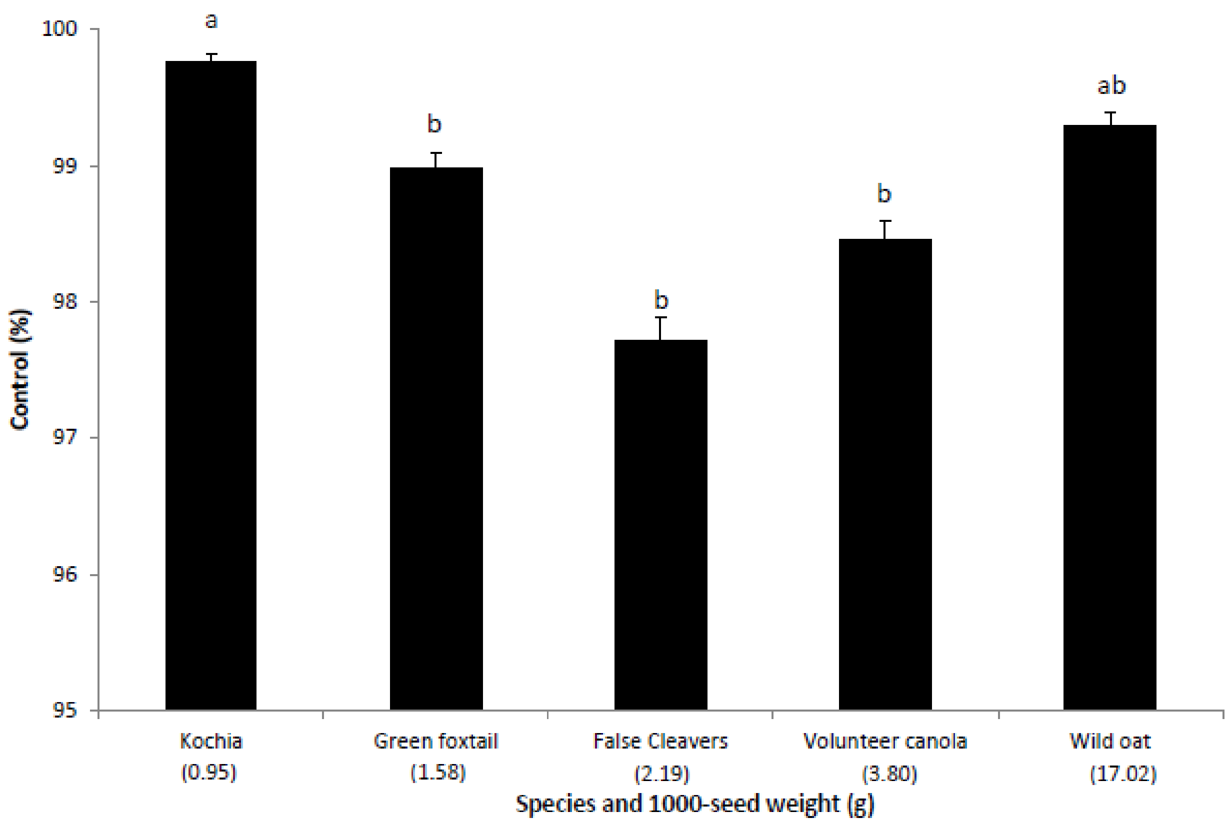

Figure 5-2. Percent control of various weed species by the Harrington Seed Destructor. The 1000-seed weight of each species is listed in brackets (g 1000 seeds^{-1}). Bars denote standard errors of the mean. Letters denote significant differences between control of species based on a Tukey adjusted comparison of means (α=0.05).

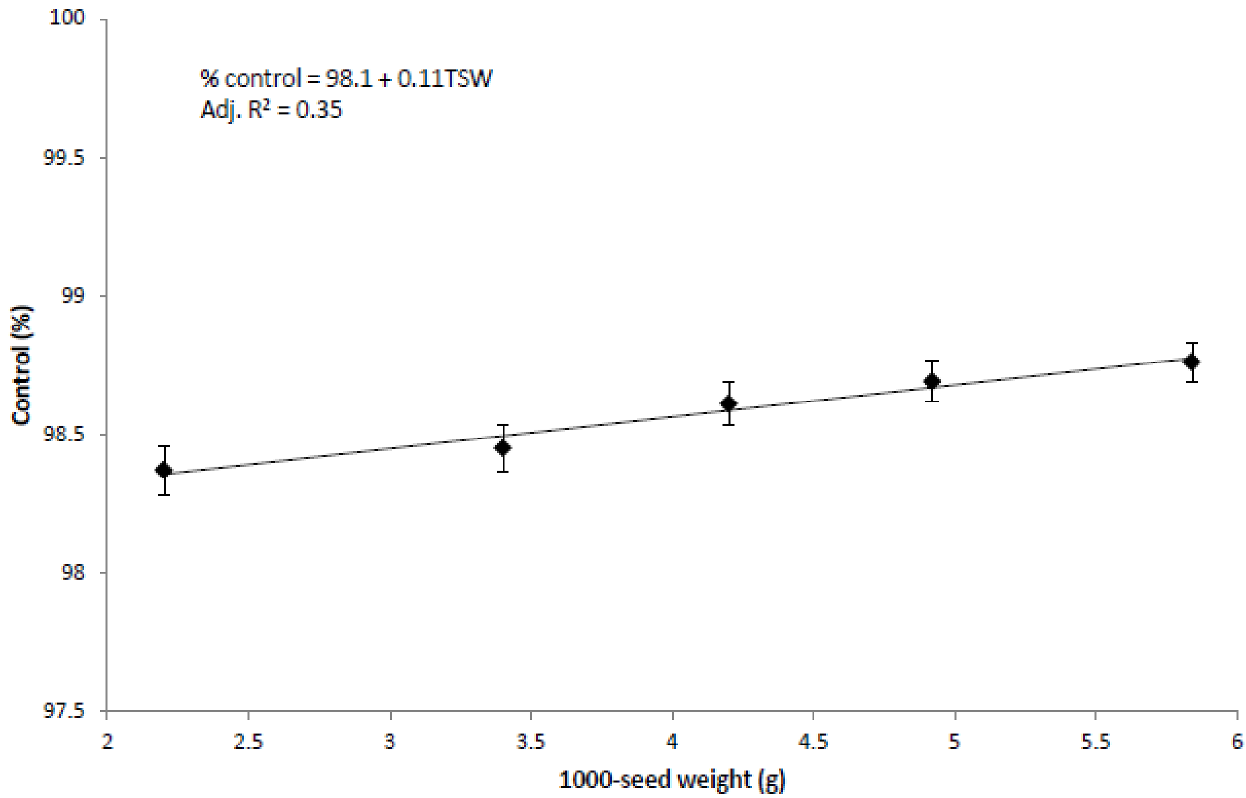

Figure 5-3. The effects of canola seed size on percent control by the Harrington Seed Destructor. Bars denote standard errors of the mean. TSW = thousand seed weight.

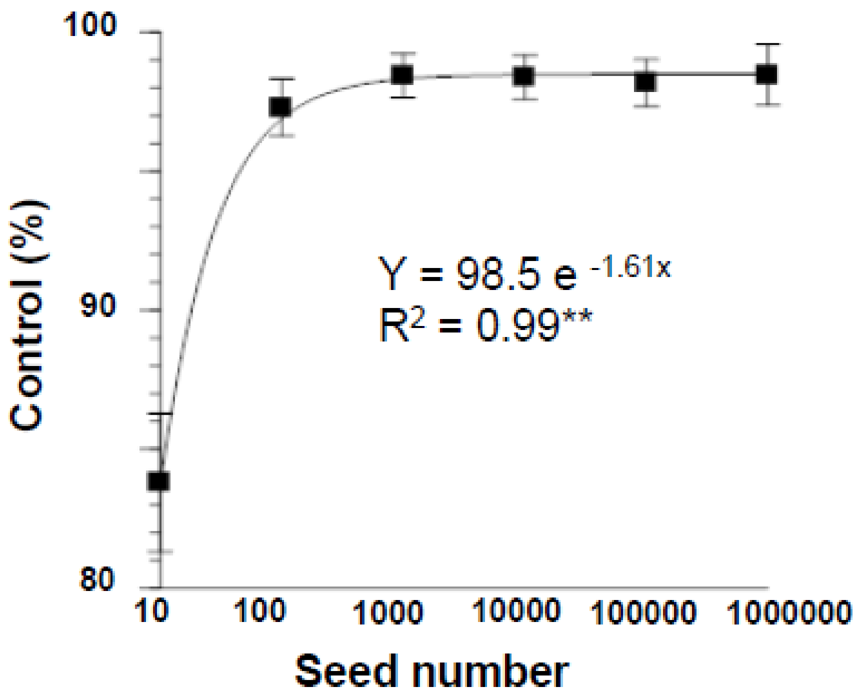

Figure 5-4. The effects of weed seed number on percent control of weed seeds by the Harrington Seed Destructor. Bars denote standard errors of the mean. ** indicates significance at p = 0.01

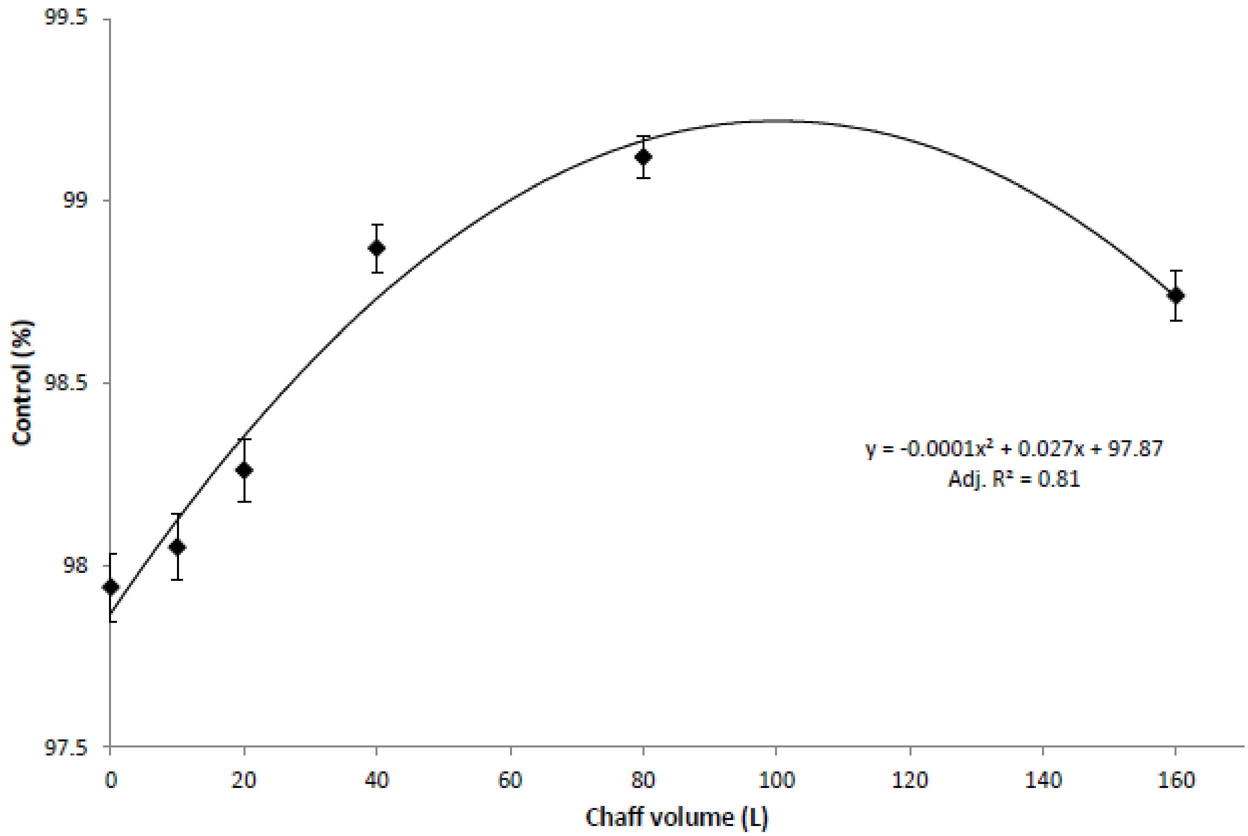

Figure 5-5. The effect of chaff volume on percent control of weed seeds by the Harrington Seed Destructor. Bars denote standard errors of the mean.

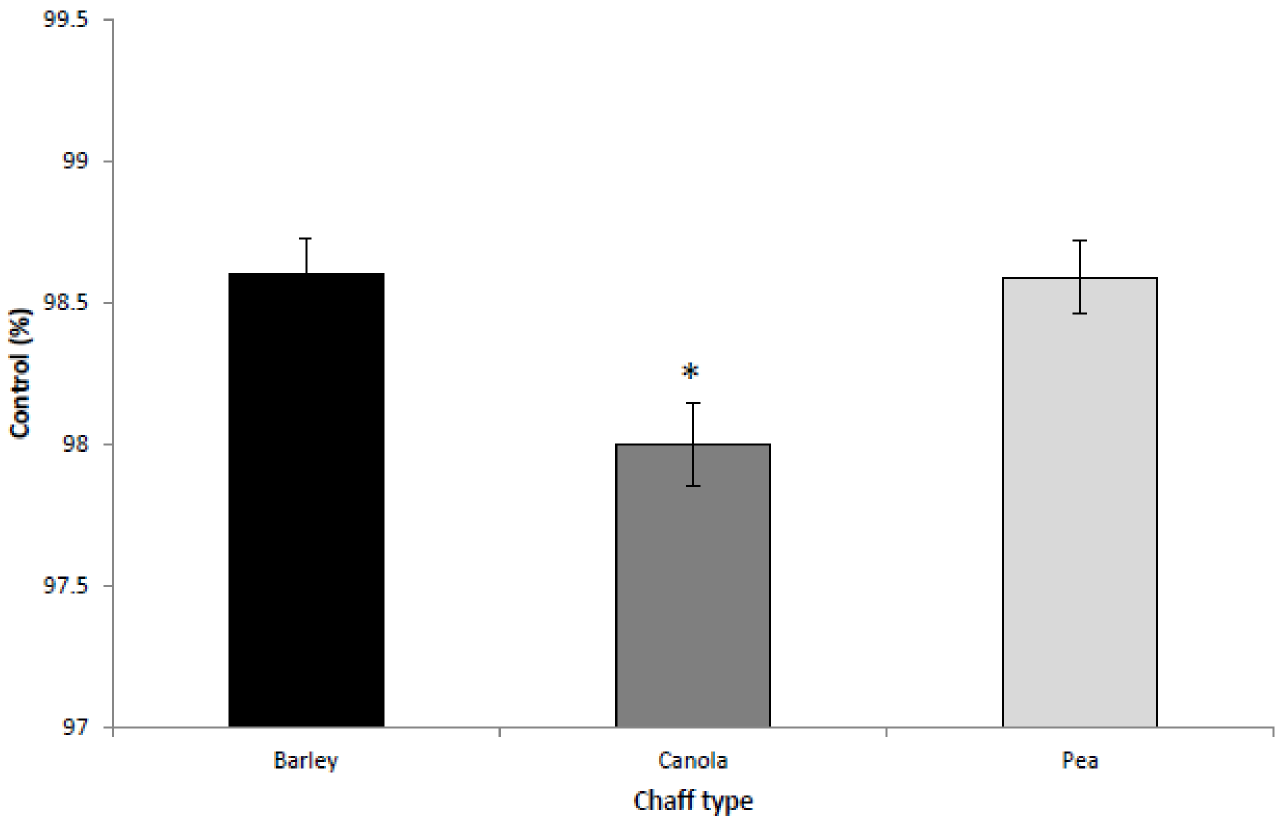

Figure 5-6. The effect of chaff type on percent control of weed seeds by the Harrington Seed Destructor. Bars denote standard errors of the mean. The asterisk depicts a significant difference between chaff types based on a Tukey adjusted comparison of means (α = 0.05).

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Chapter Six: Potential Benefit and Risk of Fluridone as a Fall Germination Stimulant in Western Canada[4]

6.1. Introduction

Herbicide resistance continues to increase globally with 478 current cases of unique resistance (Heap 2016). With each additional case of resistance, herbicide options become increasingly more limited. To exacerbate the problem, no new herbicide modes of action have been introduced in over 25 years (Duke 2012), novel herbicide research capacity is diminishing due to company mergers, and weed management in field crops continues to be primarily herbicide-based. New methods and new thinking about weed management is needed to allow continued sustainable crop production in western Canada. Targeting weeds at different or additional life cycle stages would help to increase weed management efficacy and diversity.

Increasing herbicide resistance has renewed interest in "older" herbicides such as fluridone. Fluridone is a phytoene desaturase-inhibiting (PDS) herbicide, HRAC group F1 and WSSA group 12 (Bartels and Watson 1978; Heap 2016). These herbicides block carotenoid biosynthesis, and cause bleaching and desiccation (Heap 2016). Fluridone was initially tested for use in cotton (*Gossypium hirsutum* L.) (Banks and Merkle 1979; Waldrep and Taylor 1976), but was not labeled for field use. Research into the compound declined due to residue carry-over to subsequent crops (Banks and Merkle 1979; Hill et al. 2016), availability of herbicides with more effective control spectrums, and the introduction of herbicide-resistant cotton cultivars. However, fluridone has continued to be used as an aquatic herbicide from SePro (Shaner 2014) and resistance has evolved in hydrilla [*Hydrilla verticillata* (L.f.) Royle] in the United States

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(Heap 2016). In addition to herbicidal activity, fluridone has been reported to be a germination stimulant (Goggin and Powles 2014); it has been shown to release dormancy and induce germination in laboratory studies with annual ryegrass (*Lolium rigidum* Gaud.) and tedera (*Bituminaria bituminosa* C.H. Stirt. vars *albomarginata* and *crassiuscula*) (Castello et al. 2015; Goggin et al. 2009). Biologically active fluridone residues can persist for > 385 days (Schroeder and Banks 1986), which can impact subsequent crops, but also potentially impact subsequent weed populations.

Glyphosate-resistant weed evolution in cotton in the United States has resulted in an increased need for alternate herbicide options, and a resurgence of fluridone research (Braswell et al. 2016; Cahoon et al. 2015; Hill et al. 2016). Fluridone was registered in cotton in 2016 (Braswell et al. 2016) with label restrictions based on soil characteristics, location and re-cropping intervals (Anonymous 2016a, 2016b). Fluridone carry-over may still restrict its use, although some tolerant rotational crops have been identified (Cahoon et al. 2015; Hill et al. 2016). Additionally, the dual activity of fluridone as a germination stimulant and herbicide has highlighted its potential for additional weed control uses (Goggin and Powles 2014). A compound which stimulates germination at a desired time and then exerts control may be valuable, and fluridone may be a viable option (Goggin and Powles 2014). This is especially of interest for annual weeds that persist in the soil seed bank. A chemical that can stimulate emergence from the seed bank and thereby reduce survival rates restricts a stage of the life cycle with significant impacts on overall population growth rate (Davis 2006; Tidemann et al. 2016).

Most seedlings that germinate in late fall in western Canada are killed by frost in October or November; this leaves few opportunities for weeds that emerge in the fall to survive until the following growing season. Facultative or obligate winter annual species are exceptions that typically survive fall frosts. Some winter annual species such as false cleavers (hereafter called cleavers) are significant problems in western Canada (Leeson et al. 2005). Germination stimulation in combination with winter temperatures may be enough to control some weeds, although a stimulant that also has herbicidal activity may be ideal to prevent an increase in winter annual weed competition.

A number of characteristics would be required of a compound used for both germination stimulation and herbicidal activity. Germination stimulation or weed seed dormancy would need to be sufficiently altered to affect the following year's populations of key weed species. Efficacy would need to occur shortly after fall application at economically feasible rates across a range of edaphic conditions and with low phytotoxicity to common rotational crops. The objective of this study was to determine efficacy levels of fluridone in Alberta field studies as a combination germination stimulant and herbicide. Because efficacy was studied under field conditions, fall emergence counts were used as a proxy for germination stimulant measures and spring plant population densities used as a proxy for herbicidal efficacy. In addition, rotational tolerance of common annual crops to fall-applied fluridone was determined.

6.2. Materials and Methods

This study was conducted following completion of a weed seed retention study described in Tidemann et al. (2017) at Lacombe, AB in 2014 and 2015, and St. Albert, AB in 2015. In that study, populations of wild oat, cleavers, and volunteer canola were established across crop plots in individual areas. Fababean and wheat were seeded at 30 or 60 seeds m^{-2} and 200 or 400 seeds m^{-2}, respectively in a randomized complete block design (Tidemann et al. 2017). No herbicides were applied in the previous study, so no herbicide residues were present nor was there an effect of previous herbicides on populations (Tidemann et al. 2017). For the current study, the 1x seeding rate (30 and 200 seeds m^{-2}, respectively) (Tidemann et al. 2017) of each crop was split into two smaller plots with four replicates of each chemical treatment in a split plot design. Chemical treatments included a non-treated control and 734 g ai ha^{-1} of fluridone (SePro Corporation, Carmel, Indiana). The fluridone rate is twice the rate of that used by Goggin and Powles (2014) due to relatively high organic matter content at the two study locations. The St. Albert soil was a silty clay with 12.7% organic matter and pH 7.8. Lacombe soil was a loam to clay loam with 9-10% organic matter and pH between 6.4 and 7.5. Overall, there were four treatments: two crop and two chemical treatment combinations. Fluridone was applied using a single nozzle CO_2-pressured hand-boom sprayer with a Combojet ER80-02 nozzle (Wilger, Saskatoon, SK) on October 7 in Lacombe in 2014 and 2015, and October 8 in St. Albert in 2015. Spray volume was 100 L ha^{-1}. Plot sizes were 1.2 x 11 m at Lacombe and 0.6 x 6 m at St. Albert. Treatments were applied directly to the soil without incorporation.

Beginning 1 wk after treatment application, weed density was quantified in each of the three weed sections in each plot (cleavers, wild oat and canola). Densities were determined in a 0.25-m^2 quadrat in each weed section (3 densities per plot). In the wild oat section, counts of grass weeds including wild oat and volunteer wheat were combined to account for potential errors in differentiation of one-leaf seedlings. Densities were assessed weekly until daily temperature maximums were below 5C with frost at night, or until the occurrence of snow. Density assessments began again as early as possible following snowmelt in the spring and continued until crop seeding.

To determine tolerance of common crops in central Alberta to fluridone, wheat ('Harvest'), canola ('L150' – Lacombe, 'L130'- St. Albert) and field pea ('Meadow') were seeded perpendicular to the chemical treatments in the cleavers, wild oat and volunteer canola sections, respectively. Crops were seeded on May 15, 2015 and May 6, 2016 at Lacombe and on May 19, 2016 at St. Albert. Lacombe was seeded with a ConservaPak (ConservaPak Seeding Systems, Indian Head, Saskatchewan, Canada) air drill with 23 cm row spacing while St. Albert was seeded with a Fabro plot drill (Fabro Enterprises Ltd., Swift Current, Saskatchewan, Canada) with 20 cm row spacing. Canola was seeded at 150 seeds m^{-2}, peas at 100 seeds m^{-2} and wheat at 200 seeds m^{-2}. Plant density counts were conducted following crop emergence. In addition, visual ratings were conducted 7-14 d after treatment (DAT), 21-28 DAT and 35+ DAT to assess fluridone phytotoxicity using a 0-100% injury scale where 0 is no injury and 100 is complete death. Plant biomass for both crops and weeds was harvested at ground level from the same 0.25-m^2 quadrats used for density assessments after the completion of visual ratings and prior to weed seed set. All weeds present in a section were collected for biomass, not just target weeds. Biomass samples were dried at 70 C until weight stabilized indicating no further moisture loss and then weighed. Data on weather and precipitation was acquired from weather stations located closest to the trial sites.

6.2.1. Statistical Analysis.

Crop emergence densities, and crop and weed biomass, were evaluated using Proc Mixed ANOVA in SAS 9.4 (SAS Institute, Cary, North Carolina), where location, crop, herbicide and their interactions were fixed effects and replicate was a random effect. Pre-planned contrasts were used to test for differences between fluridone-treated and untreated crops.

Weed density data were converted to a percentage of the untreated control for each assessment date (for both fall and spring assessments) within each replicate. Preliminary examination of the data showed no consistent emergence patterns over time, making regressions of any type unusable and non-informative for comparing stimulant activity of fluridone to untreated controls. Instead, ANOVA analyses using $\alpha = 0.1$ were conducted for each density assessment date in the spring and fall for both total and target weeds in each of the three weed sections for each location separately (total ANOVAs = 162). Fixed effects included crop and chemical while random effects included replicate. An LSMestimate statement was used to obtain least squares means estimates of emergence as a percentage of the untreated control for fluridone as a single factor, fluridone in fababean and fluridone in wheat. In addition, the LSMestimate statement compared these least squares means estimates to a test value of 100 to provide a contrast with the untreated emergence which had no variance (untreated emergence = 100 % of the untreated).

When the LSMestimate contrast with the test value (100) was significant ($p < 0.1$) and the fluridone estimate was greater than the untreated estimate, it was deemed a potential incidence of stimulant activity; when the contrast was significant but the fluridone estimate was less than the untreated estimate, it was determined a potential control incident. The number of potential stimulant incidents in the fall (desired stimulation timing) were evaluated out of a total of 18 (fall total and target weeds (2), weed section (3), location (3)), while the number of potential control incidents in the spring (desired control timing) were also evaluated out of 18 (spring total and target weeds (2), weed section (3), location (3)). If a contrast was significant at a single assessment date in the fall for a specific weed section at a specific location, it was assessed as a potential stimulant event; the significance did not need to occur across the entire assessment time to be considered due to potential confounding effects of stimulation and subsequent herbicidal activity. The same methodology was used when considering spring assessments which may indicate control – the control did not need to occur across the entire time range to be considered potential evidence of control. This is a less conservative evaluation of potential stimulation/control but is appropriate to determine potential activity in a field environment and also for using a product which has confounding effects.

In addition to significant contrasts, least square means estimates (LS-means) were evaluated for any instances where fluridone was greater than the untreated control estimate in all fall assessments. These instances may indicate a trend for/against stimulation activity in a highly variable weed emergence data set that limits significance. The percentage of estimates greater than the untreated in fall assessments was calculated for >100%, >110%, >125%, >150% and >200% of the untreated to allow for evaluation of trends and the scale of potential stimulation.

6.3. Results and Discussion

Weather conditions for all three site-years were dry during critical months (Figure 6-1). At all locations, precipitation following fall fluridone application was limited, which may have limited both fall weed seed germination and herbicide activity. In the 2015-2016 winter season precipitation continued to be limited at both locations (Figure 6-1). The month of April was dry in both years and both locations; Lacombe 2014-15 had 51% of the long-term average (LTA) precipitation, while Lacombe and St. Albert in 2015-2016 had 30 and 34% of the LTA precipitation, respectively. The precipitation in May of 2015-2016 for both locations shown in Figure 6-1 is somewhat misleading as minimal rain was received until near the end of May; sites were under dry conditions for most of the month. This lack of precipitation may have limited fluridone efficacy in the study.

Of the 18 possible fall stimulation events, none of them showed significant stimulation (data not shown) at $\alpha = 0.1$. However, when investigating non-significant comparisons, the LS-means estimate of fall weed densities in fluridone-treated plots was greater than that of the untreated control 77% of the time (Table 6-1), which may indicate some actual stimulant activity. Weed densities in fluridone treatments on fababean stubble were greater than with no treatment 48% of the time and 67% of the time in wheat stubble plots (Table 6-1). While having estimates greater than the untreated control may simply be variability, fluridone treatment estimates were >125% of the untreated control nearly 60% of the time and >150% of the untreated control over 40% of the time. The pattern towards potential stimulation is stronger in wheat than in fababean stubble, with over 30% of the fluridone in wheat treatment estimates >200% of the untreated control (Table 6-1). It is possible that residual nitrogen germination effects (Egley 1986) in fababean stubble disguised the fluridone germination stimulant effect. This is speculation, however, and the specific reason behind preceding crop affecting fluridone activity is not known.

Fluridone-treated populations showed the highest potential for fall stimulation in grass weeds in the wild oat section; 91% of the time, fluridone-treated weed densities were greater than the untreated control (Table 6-1). When looking at larger differences, regardless of crop, 64% of the time fluridone densities were greater than 125% of the untreated control. In wheat plots, 55% of the densities remained greater than 150% of the untreated control. Canola showed less potential stimulation in overall numbers than grass weeds (max. 64% of the time fluridone treatment estimates were greater than the untreated control). However, the differences between densities in fluridone-treated and untreated plots seemed to have a larger magnitude (up to 27% of the time fluridone treatment densities were greater than 200% of the untreated). Cleavers in fababean plots showed minimal trends towards stimulation (9% of cases where fluridone treatment densities were greater than 100% of the untreated) while 64% of the time fluridone densities were greater than 200% of the untreated control in wheat plots. Why preceding crop appeared to have such a great effect on stimulation is unclear. These trends do not definitively show stimulation, but suggest some stimulant activity sufficient to warrant further research. Research conducted in a more controlled environment may help to clarify fluridone activity. Significant stimulant activity is not evident under Canadian field conditions unlike the report by Goggin and Powles (2014) under controlled conditions. However, high organic matter content (>9%), low precipitation and variability due to field conditions could account for at least some of the difference in results.

Fluridone's potential herbicide activity could provide post-emergence weed control of both broadleaf and grass weed species (Banks and Merkle 1979). Based on significant contrasts in weed densities in the spring, 33% of the time there was significant control in fluridone treatments across site-years (data not shown). Most of these cases occurred for total weeds (5 out of 6), with cleavers controlled as a target weed in one case. With only one significant case of target weed control, differential efficacy between broadleaves and grasses is not clear. Visual evidence of herbicidal activity suggested greater efficacy on broadleaf weeds versus grass weeds. Previous research has shown activity on both broadleaf and grass weeds (Banks and Merkle 1979). Based on weed biomass, there were no significant differences at Lacombe in 2014, but there was a trend of lower biomass in each weed section in the fluridone treatments compared to the untreated plots (Figure 6-2A). At Lacombe in 2015, there was a significant decrease in weed biomass in the cleavers section, accompanied by an increase in biomass in the wheat crop (Figure 6-2B). The wheat crop was established in the cleavers section of the plot and so biomass differences were likely associated with decreased competition. At St. Albert in 2015, there were significant differences in both crop and weed biomass for every crop and weed except wheat (Figure 6-2C). Weed biomass was consistently reduced after fluridone treatment regardless of species, with the largest decrease occurring in the volunteer canola section. The field pea crop, which was grown in the canola section, showed a large biomass increase, possibly associated with the reduction in weed competition in that section. The canola crop was also impacted, with a significant biomass reduction (Figure 6-2C).

In addition to a biomass reduction, canola crop emergence densities were significantly reduced at St. Albert in 2015 (Figure 6-3). Visual estimates consistently showed greater than 90% injury of the canola crop after fluridone treatment at this location (data not shown). Fluridone appears to have high levels of herbicidal activity on canola. The same injury was not observed at Lacombe in either year. While this could be due to use of different canola cultivars, it is more likely due to lack and timing of precipitation. Limited precipitation in April and May of the 2014-2015 study at Lacombe limited fluridone activity (Figure 6-1); very little visual evidence of fluridone activity was observed. In the Lacombe 2015-2016 trial, the amount of precipitation was not as limiting for activity. However, the timing of precipitation might have resulted in different injury levels than St. Albert. The canola crop in Lacombe emerged under dry conditions and was established at the time of precipitation; the small proportion of seeds that germinated from late-May precipitation exhibited fatal fluridone symptoms. St. Albert was seeded later than Lacombe, resulting in canola emergence during the period of precipitation and higher crop injury levels, likely due to increased fluridone availability in soil water and increased herbicide activity on less mature canola seedlings. These results suggest that timing and amount of precipitation may be critical determinants of canola crop safety to fluridone. Wheat and pea biomass were not negatively affected by fluridone, but minor injury symptoms were observed on both crops at St. Albert in 2015-2016 (data not shown).

Some germination stimulant activity, based on plant emergence, may be occurring as a result of fluridone application, but variability between sites and years and the confounding effects of herbicidal activity make conclusions difficult. For example, lower spring weed biomass could be a result of fall germination stimulation followed by winterkill, spring herbicidal activity, or both effects combined. The time of precipitation events, and the resultant chemical activation, could influence germination and germination stimulation prior to winter, which may decrease populations, or in spring, which may increase weed populations. Fluridone showed herbicidal activity, reducing biomass of volunteer canola, cleavers and wild oat, although biomass differences were not significant for all site-years. A higher than typical rate of fluridone was used to ensure activity on high organic matter soils, but may have also increased crop phytotoxicity. Fluridone phytotoxic effects on wheat and canola have been previously reported (Goggin and Powles 2014; Hill et al. 2016; Shea and Weber 1983), and the prevalence of these crops in western Canadian rotations is of concern, particularly in areas with lower organic matter content than the study locations. While fluridone may provide an effective germination stimulant and herbicide tool combined, the rate structure, consistency of efficacy and crop tolerance issues would need further research before it proves to be a viable tool in western Canada. Risks of injury to subsequent crops by fluridone outweighed the benefit of germination stimulant or herbicidal control of herbicide-resistant weeds under the conditions of this study. Future studies should include fluridone effects on weed populations over multiple years to minimize the effects of variability in populations within a year. An effective rate structure of fluridone could also be better defined as it is possible that the high rates used in this study were the cause of crop injury; however, lower rates may also further limit the stimulant activity which was not observed to be significant in this study. Studies that include removal of emerged plants may also help to eliminate the confounding effects of stimulation and herbicidal control. In the broader context, whether it is stimulation followed by winterkill or herbicidal activity that kills the weeds is unimportant, as long as the population is being managed. However, knowledge of which effect is occurring is helpful for identifying the targeted stage in weed life cycles, to determine if the seed bank is being targeted or if fluridone is simply a new herbicide option for some crops.

Table 6-1. Percentage of fall assessments at all site-years and locations where least-square estimates of weed densities treated with fluridone were greater than the untreated control (>100). Percentages are calculated for fluridone alone as a factor, fluridone in fababean and fluridone in wheat.

Densities	Sample size	Emergence	Fluridone	Fluridone in fababean	Fluridone in wheat
		% of untreated		---%---	
All calculable	66 (65 for fluridone in fababean)	>100	77	48	67
		>110	67	46	56
		>125	61	34	53
		>150	41	22	45
		>200	20	11	32
Total weeds in all sections	33	>100	82	45	70
		>110	70	45	58
		>125	61	30	55
		>150	36	21	42
		>200	21	12	30
Grasses (wild oat section)	11 (10 for fluridone in fababean)	>100	91	73	82
		>110	73	73	55
		>125	64	55	55
		>150	36	27	55
		>200	0	0	18
Canola (canola section)	11	>100	64	64	45
		>110	55	55	45
		>125	55	45	36
		>150	45	27	27
		>200	18	27	18
Cleavers (cleavers section)	11	>100	64	9	64
		>110	64	9	64
		>125	64	9	64
		>150	55	9	64
		>200	36	0	64

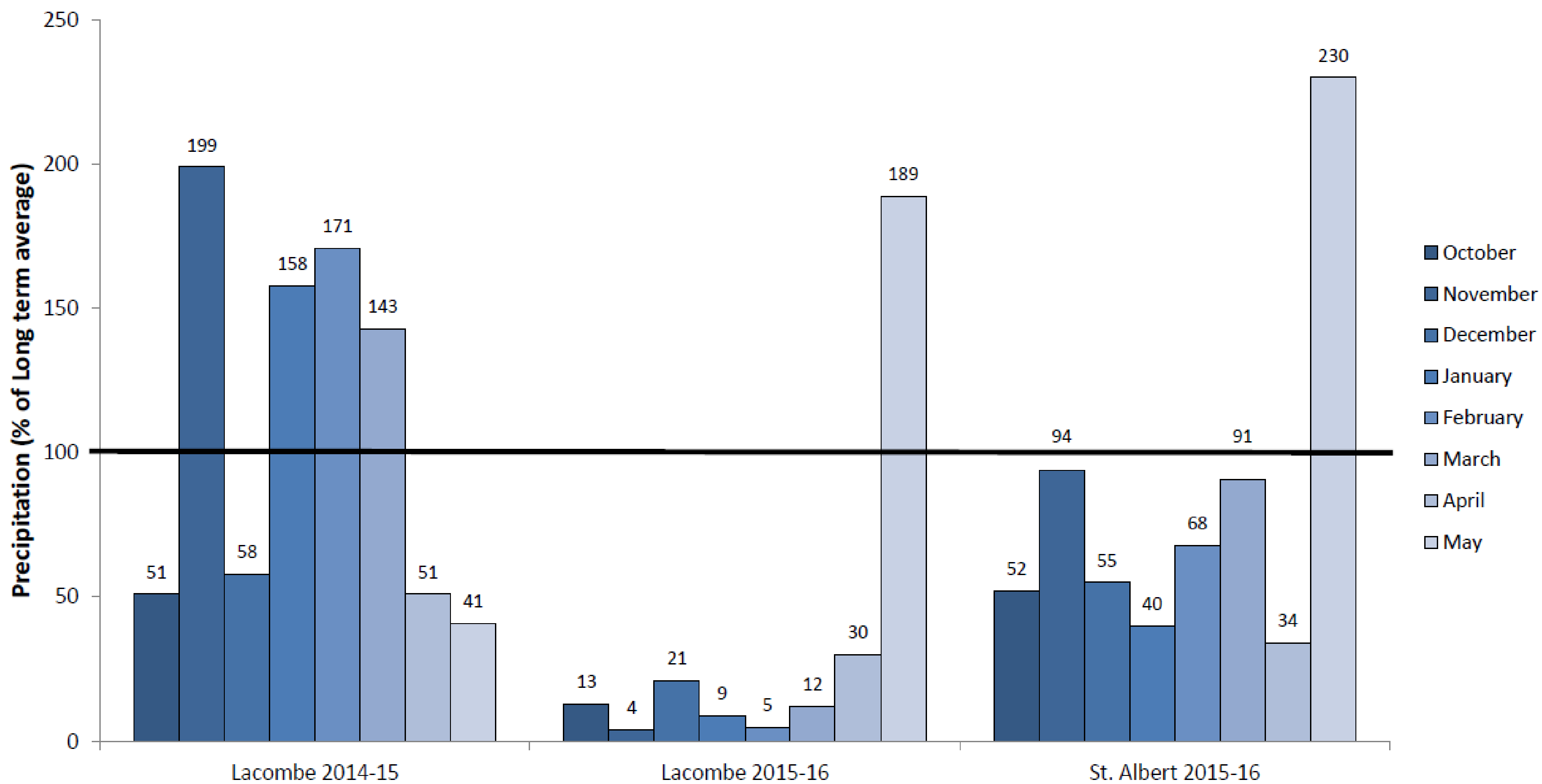

Figure 6-1. Precipitation as a percent of the long term average at each site year from October through May. The bold line indicates 100% of the long term average precipitation. Data values for each month are labelled above their respective bar.

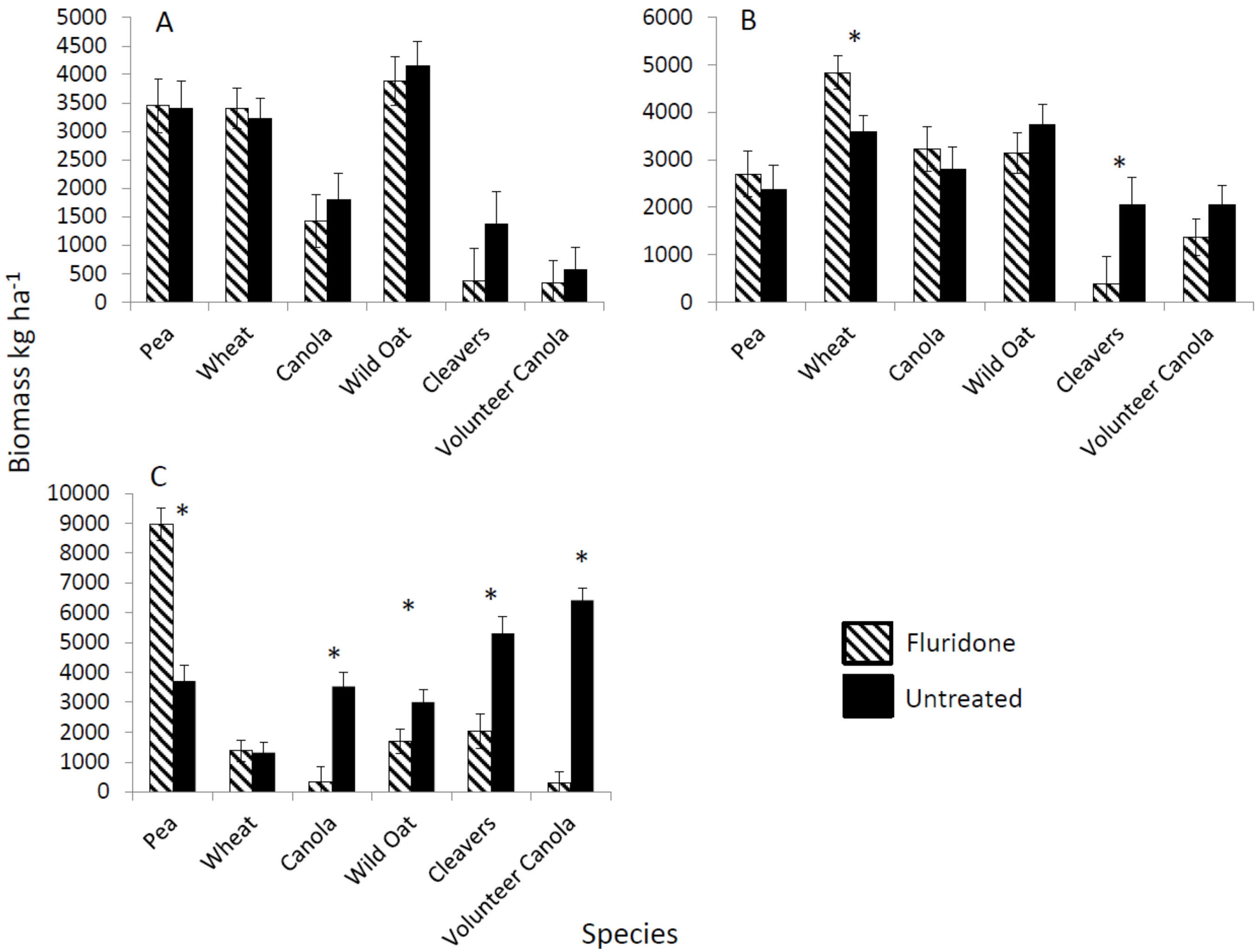

Figure 6-2. Crop and weed biomass at A) Lacombe 2014-2015, B) Lacombe 2015-2016 and C) St. Albert 2015-2016. Asterisks indicate significant differences between fluridone and untreated control treatments within a species based on single degree of freedom contrasts ($p < 0.05$) (bars denote SE).

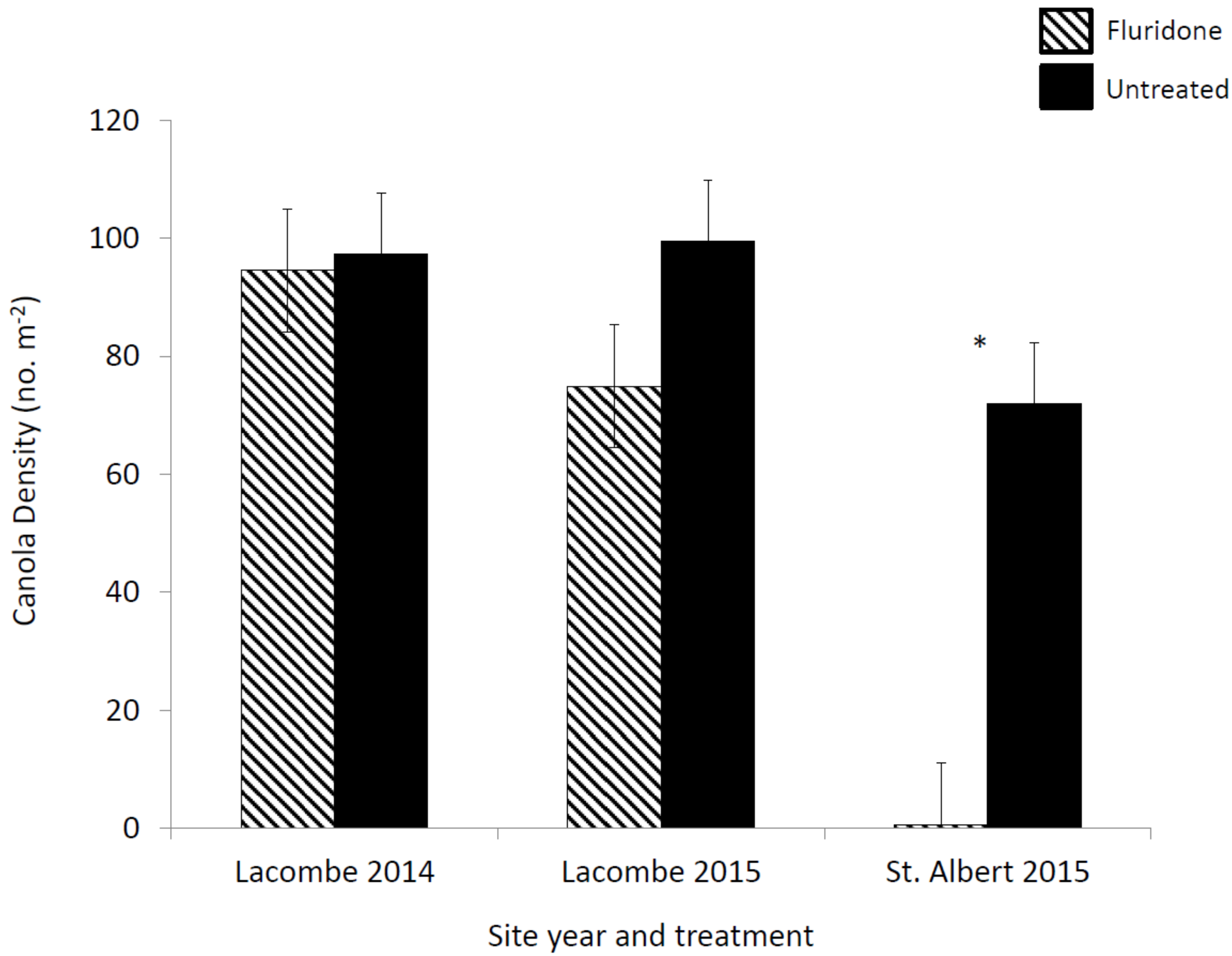

Figure 6-3. Canola crop density at emergence in fluridone and untreated control plots for each site-year. Asterisks indicate significant difference between the fluridone-treated and untreated plot densities based on single degree of freedom contrasts ($p < 0.05$) (bars denote SE).

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Chapter Seven: General Discussion and Conclusions

7.1. Summary of Results

Research in this thesis has investigated the possibility of targeting non-seedling life cycle stages of economically important weeds. Seed retention over time and height of seeds retained on the plant at the time of harvest in relation to harvester cutting height were used to identify the potential of key target weeds for management by harvest weed seed control (HWSC). A demographic model was used to further investigate the potential impact of harvest weed seed control on wild oat population growth rates based on seed retention and life cycle data. Once some target weeds were identified as HWSC candidates with technologies such as the Harrington Seed Destructor (HSD), the effects of some crop or seed parameters on HSD efficacy was evaluated. The HSD was therefore tested for management capability on a number of weed species, as well as for its ability to function and manage weed seeds with different chaff types, a range of chaff volumes, a range of seed sizes and a range of seed number.

Fluridone was investigated for its potential as a germination stimulant and herbicide combination for controlling weed seeds that are shed from parent plants prior to crop harvest. The fluridone trials were initiated to research management opportunities for those weeds that are unlikely to be affected by HWSC populations.

This research has identified volunteer canola and cleavers as good and potential candidates for HWSC technologies, respectively. It has identified wild oat as a poor candidate for HWSC with that conclusion supported by demographic modeling. Additional life cycle stage targets for wild oat were identified using a demographic model. Fluridone was evaluated for potential as a germination stimulant and risks of fall applications of the product were identified that may outweigh the benefits of fluridone as a weed management tool.

7.2. Results Summarized by Research Objective

7.2.1. Determine the suitability of driver weed species for harvest weed seed control through measures of seed retention and height of seed retention.

Seed retention over time and height of seed retention for target weeds relative to ground level and assumed harvest height were described in Chapter 3, a version of which has been accepted for publication in Weed Science. A randomized complete block design trial was established in 3 locations in 2 years to measure seed retention and retained seed height as affected by crop competition. Normal and doubled seeding rates of wheat and fababean were used to provide a range of crop competitiveness. Seeds were collected from the plots as they were shed from the plant and plants were sampled at wheat swath timing, wheat harvest timing and fababean harvest timing to ascertain the number of seeds retained on the plant. Harvested plants were sectioned into 0 – 15 cm, 15 – 30 cm, 30 – 45 cm, and > 45 cm above ground level to determine seed retention height. The effects of crop competition on seed retention were not well defined; where crop competition had a significant effect on seed retention, it did not consistently decrease retention as expected but was variable. Crop competition also did not consistently increase the height of seed retention. While wild oat produces seed well above the harvester cutting level, its seed retention was variable with an average of 56% retained at the time of weed swathing. Overall, it was identified as a poor candidate for harvest weed seed control. Cleavers seed retention was highly variable but the majority of the seed was retained >15 cm above ground level (suggested harvester cutting height in Australia) making it an intermediate potential target for harvest weed seed control. Volunteer canola had high seed retention and seed was produced well above harvester cutting level, suggesting it could be a good target for harvest weed seed control. The collected data supported the initial hypotheses that seed retention would vary by species and location, and height of seed retention would vary by species. However, the hypothesis that crop competition would affect seed retention over time and height of seed retention was not supported by the data; the inconsistencies in competition effects did not allow determination of a clear effect. The overall suitability of tested weeds for HWSC was volunteer canola > cleavers > wild oat. Environmental conditions each year may have an impact on seed retention and therefore efficacy of HWSC. This chapter helped identify the potential benefit of HWSC on managing populations of problem weeds in western Canada. However, sole reliance on HWSC will likely cause a shift in weed phenology leading to earlier shedding, and lower growing weeds. These changes are likely associated with fitness penalties and their timeline of evolution is not known. However, it is key that HWSC techniques are used in an integrated weed management system to ensure continued success in managing weeds over time.

7.2.2. Determine potential target life cycle stages of wild and the potential effects of harvest weed seed control on wild oat population growth rate.

This research objective was investigated in Chapter 4, a version of which was published in Weed Science in 2016 (Tidemann et al. 2016). A periodic matrix model was developed using data collected from a long-term, rotational field study conducted in Lacombe, AB (Harker et al. 2009, Polziehn 2011). Treatments with extremes of management were selected from the trial, and population growth rates calculated for each of those treatments in each of two years. Prospective and retrospective analyses were conducted on the model. The model was also rearranged to solve for the proportion of newly shed seed survival required for a given growth rate. All of the populations in selected treatments had $\lambda > 1$, indicating growing populations. Elasticity analysis was used to determine the proportional change in the growth rate as a result of a proportional change to a vital rate. The analysis indicated that changes in overwinter seed bank survival had the most impact on overall population growth rate, followed by seedling survival, fecundity and the survival of newly shed seed. The latter three parameters had an elasticity of 0.63-0.86, depending on treatment, indicating that a 10% reduction in the survival of newly shed seed would have a 6-9% impact on overall population growth rate. This indicates that harvest weed seed control technologies which are designed to target the survival of newly shed seed, would be relatively impactful on the wild oat life cycle if they are controlling large percentages of the seed. The survival of newly shed seeds is an important parameter in the life cycle, until that survival is reduced to 10-30%, at which point survival in the growing season seed bank becomes more important. When averaged across treatments, HWSC would need to eliminate >80% of newly shed seed to create a stable, non-growing population. Data from this chapter supported the hypothesis that seed bank survival is a significant factor in wild oat population growth rate and the seed bank was identified as a good target for future management methods. Additionally, survival of newly shed seed and fecundity were also highlighted as potential management targets. As harvest weed seed control would need to eliminate 80% of newly shed seed, but relatively fewer seeds are available at harvest as measured in Chapter 3, it is unlikely that the addition of HWSC to management systems would cause wild oat population decline. This creates a limitation for HWSC adoption in western Canada as effectiveness on the dominant herbicide resistant and economically important weed is limited.

7.2.3. Determine the effects of weed species, weed seed size, weed seed number, chaff volume and chaff type on the efficacy of the Harrington Seed Destructor

This research objective was investigated in Chapter 5, a version of which has been accepted for publication in Weed Science. Stationary threshing trials were conducted with the Harrington Seed Destructor (HSD) to determine its potential under varying crop and seed parameters. Many producers are interested in the HSD's ability to manage specific problem weed species on their farm. Therefore, 10,000 seeds of some problematic weed species were mixed with 20 L of barley chaff and processed by the machine to determine its ability to devitalize them. These species included: volunteer canola, kochia (*Kochia scoparia* L. Schrad.), green foxtail (*Setaria viridis* L. Beauv.), cleavers and wild oat. There were significant differences between species, however, control ranged only from 97.7% to 99.8%. While this supports the initial hypothesis that efficacy of the HSD will vary by species, the high efficacy across all species indicates limited biological differences would be observed in the field.

To determine the effects of weed seed size, a single volunteer canola variety was hand sieved to separate seeds by size resulting in a thousand-seed weight range of 2.2g to 5.8g. This allowed a comparison based on seed size that limited confounding factors as much as possible. After sieving, 10,000 seeds of each size were mixed with 20L of chaff for processing by the HSD. There was a significant linear regression with control of seeds increasing as the thousand-seed weight increased, supporting the original hypothesis made in Chapter 1. However, with > 98% seed devitalization across all seed sizes, the biological impact of decreased devitalization on small seeds is likely limited.

Weed seed number impacts on HSD efficacy were evaluated with 10 to 1 million seeds of canola distributed in 20L of barley chaff. This investigated the potential ability of the HSD to manage larger weed densities or patches. There was a significant exponential reciprocal regression of percent seed devitalization as the seed number increased. Lower devitalization was observed with 10 seeds (84%), but by 100 seeds over 97% of the weed seeds were devitalized. While this could be due to deflection resulting in an increased number of impacts per seed with increased seed densities being processed at a time, it is likely that 10 seeds provided an inadequate sample size on which to measure control and viability. Small patches or low weed seed densities would likely not compromise population control levels with the HSD in the field. These results did not support the initial hypothesis that control would decrease with an increase in seed number; there is no evidence to support decreased control with increased seed number from this study.

Chaff volume treatments each included 10,000 volunteer canola seeds. These seeds were processed without chaff, with a half pail of chaff, and up to eight pails of chaff (0 L – 160 L). The 10,000 seeds were evenly dispersed through the chaff for each treatment. There was a significant quadratic relationship of devitalization by the HSD with increasing chaff volume, with control initially increasing and then declining. However, the scale of this regression was quite small with control ranging from just under 98% to just over 99%. This small range of devitalization is unlikely to show significant impacts on control in fields with different crop volumes. This relationship does not support the initial hypothesis that increased chaff volume will decrease control, as control initially increases. Chaff volume is unlikely to cause control concerns in the field.

To ensure that the HSD is effective in different crops, 10,000 canola seeds were distributed through 20 L samples of barley, canola and pea chaff. These samples were then processed by the HSD and evaluated for percent devitalization. There were significant differences in control of volunteer canola when processed in different chaff types, which rejected the initial hypothesis of equal control regardless of chaff type. Canola seeds that were processed in canola chaff showed higher survivability than when processed in barley or pea chaff. This may be due to the composition of the chaff (i.e. pods) being adapted to provide protection to canola seeds. However, it is more likely that there was an underlying, and unaccounted for presence of volunteer canola in the canola chaff, in addition to the volunteer canola that was counted and added. This would skew the calculations of devitalization and would have confounded the differences between crops. However, with > 98% control of volunteer canola seeds in all chaff types, control is likely to be high regardless of crop type.

7.2.4. Determine the potential for fluridone to be used as a germination stimulant in western Canada.

This research objective was investigated in Chapter 6, a version of which has been preliminarily accepted for publication in Weed Technology. Preliminary experiments (not reported in this thesis) were conducted in the greenhouse to determine if fluridone had stimulant activity; however, lack of dormancy in weed seeds used confounded the results of this experiment and lead to the experiment being conducted in the field. In the field, confounding effects of both stimulation and control exerted by fluridone resulted in highly variable weed populations over time. Some emerging weeds were fatally controlled by herbicidal effects of fluridone limiting the ability to account for new germinations each week. While there was a trend for higher weed densities in fluridone treatments when compared to untreated areas, differences were not significant. This provided weak support for the hypothesis that fluridone application would increase fall weed emergence. In spring counts, weed populations were reduced in 33% of cases, providing weak support for the hypothesis that fluridone application would decrease spring weed populations. Canola tolerance of fluridone application was poor when moisture was received when the canola was relatively young, resulting in severe injury and crop death. Wheat and pea crops also showed minor injury when moisture was received early in their growth. This highlights potential carry-over risks, particularly during wet years in early crop stages. These findings led to rejection of the initial hypothesis that fall fluridone applications would not affect subsequent crops. There were also impacts on crop biomass where weed populations had been managed, indicating indirect competition effects on subsequent crops in addition to direct crop tolerance effects. With significant control of a target weed in one case, it is not possible to determine whether there is differential efficacy of fluridone between broadleaf and grass weeds. Overall, the potential carry-over effects may indicate that risks of fall fluridone applications outweigh the benefits, based on inconsistent and primarily non-significant stimulation effects.

7.3. Future Research

- Potential target weeds have been identified for HWSC methods. However, the identification of targets through biological measures of seed retention need to be confirmed through larger scale trials where the management methods are employed. This will determine whether small plot results are indicative of producer fields. This is particularly important for wild oat as the primary herbicide resistant and economic problem weed. Additional recent studies have also identified wild oat as a poor HWSC target (Beckie et al. 2017; Burton et al. 2016; Burton et al. 2017), but shown much higher retention levels of the weed. Earlier maturing crops than used in the studies in this thesis may increase the proportion of wild oat available for HWSC, however, there have been some observations that seem to indicate wild oat synchrony with crop maturity which would contradict any benefit of growing early maturing crops. It is important to verify the seed retention and modelling results to determine whether HWSC can effectively aid in management of wild oat populations, and to ensure that a potentially useful tool is not unduly discarded.

- The demographic model conducted in Chapter 4 indicated that over-winter seed bank survival is a crucial life cycle parameter for wild oat. Determining a method to target the over-winter seed bank should be a focus of ongoing research to continue to effectively manage wild oat.
- The demographic model also indicated that fecundity and summer seed bank survival could make good management targets in wild oat. Investigations into additional seed predation and prevention of seed production will be critical to continued effective management in the face of herbicide resistance.
- Models should be created for other target weeds such as cleavers to determine the potential impact of new management techniques on population growth rate. Limited demographic information is available on cleavers and experimental field trials could be designed to investigate this species.
- Demographic models could be conducted for additional problematic species to identify impactful life cycle stages for control. This may require field trials to collect parameter data prior to model parameterization. These demographic models could be particularly useful for herbicide resistant weed species to identify where research on new management techniques should focus.
- The Harrington Seed Destructor has been demonstrated to effectively manage those seeds that are introduced into it. Field testing of the machine will verify these results. However, it is important to also test other methods of HWSC, particularly those that are more climate dependent such as the chaff deck and narrow windrow rotting. Both of these methods place the chaff in specified rows. While equipment traffic provides some control, anecdotally very few weeds

emerge from these chaff rows in Australia due to decomposition. With very different climates it is important that Canadian producers know if the same decomposition effects would occur on chaff lines or chaff rows used in western Canada.

- Future studies with fluridone should investigate the effects of fall fluridone applications on weed populations over multiple years. This would help to identify treatment effects, even with the confounding herbicidal and germination stimulant activity of the product. Additionally, more work is needed on this product to determine crop safety on different soils in different environmental conditions. The rate structure also needs to be defined so that the lowest effective rate is used for stimulation to prevent or minimize carry over injury to the subsequent crops.
- New machinery such as the CombCut™ or the Weed Surfer™ may provide opportunities to prevent seed set of weeds in crop. There is potential to selectively control seedling broadleaf weeds in cereal crops or impact the fecundity life cycle stage through prevention of seed set for weeds that produce seeds above the crop canopy. These machines are being marketed for the organic agriculture sector, but may provide herbicide resistance management options for the conventional agriculture sector as well. They provide an opportunity to target the additional fecundity life cycle stage. Efficacy of these types of machines and suitable targets should be evaluated in western Canada, as well as evaluating the potential of these machines to contribute to weed management in a cropping system study.

- Long term rotational trials should be conducted on a cropping systems basis that includes cultural methods such as crop rotations, increased seeding rates and early cut silage in combination with novel technologies such as HWSC methods and strategic inter-row tillage. A study by Harker et al. (2016) has shown that wild oat densities can be managed as effectively with cultural methods over a 5 year time period as in a non-diverse rotation relying solely on herbicides for weed control. However, wild oat is not the sole species in fields but grows in diverse populations with other species. These cultural methods need to be evaluated for a number of weed species to ensure that the management tactics employed do not simply result in a species shift away from wild oat. Addition of novel technologies such as chaff collection or strategic tillage may help prevent species shifts. These longer term studies should be designed to include weed control methods at as many life cycle stages as possible, or at the highly impactful life cycle stages as a minimum. Theoretically, this would provide the highest probability of managing the populations with limited species shift or resistance mechanisms evolving to any of the management techniques.
- Gene drives have been suggested as an option, particularly with outcrossing species, to introduce sterility and stop weed seed bank inputs, particularly for herbicide resistant weeds. However, with other organisms, resistance has developed to the gene drives (Callaway 2017) so the temporal effectiveness of this methodology is unclear. Research should study the applicability of gene drives to herbicide resistance, and the resilience of the method over generations.

- The use of tillage in Western Canada has been limited due to the adoption of conservation tillage practices. However, inter-row crop tillage, now achievable in narrow row crops with vision guidance, would allow tillage management of inter-row weeds while maintaining ground cover with the growing crop and leaving stubble for snow capture and ground cover during the non-growing seasons. Research on inter-row crop tillage weed management efficacy and the suitability of this practice for western Canada is needed. Quantification of soil health changes due to introduction of strategic inter-row tillage is needed to determine if benefits of conservation tillage would be lost.
- Precision agriculture has provided new opportunities in weed control such as strategic inter-row tillage (above), undersown inter-row cover crops/inter-crops, and site-specific herbicide applications. As the equipment and technology improves, these opportunities become more available and more efficient. Use of cover-crops in western Canada has been limited due to limited moisture and yield losses due to competition with the crop, in addition to the short growing season. The ability to undersow a cover or relay crop will limit the competition the main crop faces which may limit yield loss. Research should be conducted on the potential for undersown cover crops or relay crops in combination with inter-row tillage as it provides an opportunity to implement two non-chemical weed management strategies at once.

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Appendix A

Supplementary tables for Chapter 3. Due to landscape layout, tables begin on the next page.

Table A-1. Regression parameter estimates for wild oat seed retention in wheat or fababean (combined across seeding rate or presented by seeding rate) (see Figure 3-1). Site-years are abbreviated as follows: La = Lacombe, Sc= Scott and StA= St. Albert (number indicates 2014 or 2015). Numbers in parentheses are standard errors; standard errors of '.' indicates the estimate was restricted by the bounds imposed on the model and therefore non-estimable.

Site-year/ Trt	Line type	Sd. rate	Upper asymptote (D)	Lower asymptote (A)	Slope (B)/(M)	50% seed loss date (GDD)	Intercept	Upper limit (L)	Segment 1 slope(U)	Segment 2 slope(V)	GDD breakpoint (R)	Adj. R2
La14/ Faba	Logistic		99.6 (2.94)	21.4 (3.22)	-19.8 (3.03)	1064 (8)						0.84
La14/ Wheat	Logistic		99.5 (1.60)	20.3 (4.68)	-22.7 (3.12)	1062 (7)						0.95
La15/ Faba	Logistic		100 (.)	10.1 (8.42)	-11.5 (1.11)	1123 (22)						0.93
Sc14/ Faba	Logistic		100 (.)	39.2 (3.51)	-21.6 (3.65)	1094 (10)						0.72
Sc14/ Wheat	Logistic		100 (.)	27.2 (5.73)	-21.8 (4.21)	1062 (12)						0.76
Sc15/ Faba	Logistic		100 (.)	34.3 (4.97)	-15.1 (3.10)	1100 (18)						0.71
StA14/ Faba	Logistic		98.9 (2.56)	10.6 (1.57)	-30.0 (4.00)	1033 (4)						0.93
StA14/ Wheat	Logistic		100 (.)	0 (.)	-19.1 (1.25)	1000 (4)						0.89
StA15/ Faba	Logistic		100 (.)	28.6 (7.55)	-12.9 (2.36)	1078 (25)						0.78
StA15/ Wheat	Logistic		100 (.)	0 (.)	-10.7 (0.78)	1053 (7)						0.82
La15/ Wheat	Segment							97.5 (2.27)	0.02 (0.02)	-0.14 (0.006)	871(20)	0.90
Sc15/ Wheat	Linear	1x			-0.17 (0.01)		240.4 (14.3)					0.79
		2x			-0.14 (0.01)		207.3 (9.14)					

Table A-2. Regression parameter estimates for cleavers seed retention in wheat or fababean (combined across seeding rate or presented by seeding rate) (see Figure 3-2). Site-years are abbreviated as follows: La = Lacombe, Sc= Scott and StA= St. Albert (number indicates 2014 or 2015). Numbers in parentheses are standard errors; standard errors of '.' indicates the estimate was restricted by the bounds imposed on the model and therefore non-estimable.

Site-year/ Trt	Line type	Sd. rate	Upper asymptote (D)	Lower asymptote (A)	Slope (B)/(M)	50% seed loss date (GDD)	Intercept	Upper limit (L)	Line segment 1 slope(U)	Line segment 2 slope(V)	GDD breakpoint (R)	GDDsq (quadratic)	Adj. R2
StA14/ Faba	Logistic		95.3 (1.56)	12.4 (2.17)	-33.3 (3.17)	1116 (4)							0.94
StA14/ Wheat	Logistic		97.1 (3.42)	31.3 (32.72)	-31.9 (19.29)	1125 (40)							0.60
StA15/ Faba	Logistic	1x	92.2 (2.01)	0 (.)	-30.9 (3.43)	1107 (6)							0.94
		2x	96.1 (2.31)	0 (.)	-17.9 (1.47)	1083 (7)							
StA15/ Wheat	Logistic		94.9 (2.11)	0 (.)	-16.6 (1.36)	1060 (6)							0.89
La14/ Faba	Segment	1x						99.0 (4.16)	0.004 (0.03)	-0.13 (0.02)	1031 (39)		0.70
		2x						99.7 (3.40)	0.001 (0.02)	-0.21 (0.02)	1052 (21)		
La14/ Wheat	Segment							99.3 (1.68)	0.002 (0.011)	-0.18 (0.04)	1082 (16)		0.90
La15/ Faba	Segment							97.2 (3.79)	0.02 (0.03)	-0.0007 (0.0002)	946 (39)		0.65
La15/ Wheat	Segment							96.9 (1.91)	0.02 (0.01)	-0.0004 (0.0002)	942 (40)		0.67
Sc15/ Faba	Segment	1x						95.8 (1.54)	0.0001 (0.00004)	-0.12 (0.02)	1134 (21)		0.69
		2x						99.2 (2.30)	0.00003 (0.0001)	-0.04 (0.01)	1035 (71)		
Sc15/ Wheat	Segment							93.8 (7.51)	0.02 (0.06)	-0.13 (0.04)	1006 (77)		0.27
Sc14/ Faba	Linear	1x			-0.02 (0.004)		123.7 (4.00)						0.28
		2x			-0.06 (0.01)		150.3 (11.64)						
Sc14/ Wheat	Quadratic				0.32 (0.20)		-51.9 (107.41)					-0.0002 (0.0001)	0.22

Table A-3. Regression parameter estimates for canola seed retention in wheat or fababean (combined across seeding rate or presented by seeding rate) (see Figure 3-3). Site-years are abbreviated as follows: La = Lacombe, Sc= Scott and StA= St. Albert (number indicates 2014 or 2015). Numbers in parentheses are standard errors; standard errors of '.' indicates the estimate was restricted by the bounds imposed on the model and therefore non-estimable.

Site-year/ Treatment	Line type	Seeding rate	Upper limit (L)	Line segment 1 slope(U)	Line segment 2 slope(V)	GDD breakpoint (R)	Slope	Intercept	Adj. R2
La14/Faba	Segmented	1x	99.7 (0.46)	0.001 (0.002)	-0.11 (0.02)	1196 (10)			0.59
		2x	100.0 (0.54)	0.0001 (0.003)	-0.014 (0.006)	1124 (57)			
La15/Faba	Segmented	1x	99.1 (0.48)	0.003 (0.002)	-0.05 (0.009)	1137 (17)			0.49
		2x	99.8 (0.48)	0.001 (0.002)	-0.02 (0.01)	1105 (41)			
Sc14/Faba	Segmented		98.6 (0.70)	0.005 (0.005)	-0.024 (0.004)	1111 (36)			0.41
Sc15/Faba	Segmented		100.00 (0.27)	0.00001 (0.002)	-0.006 (0.002)	1093 (59)			0.21
StA14/Faba	Segmented	1x	98.8 (0.79)	0.007 (0.006)	-0.09 (0.004)	1058 (11)			0.91
		2x	99.6 (0.83)	0.003 (0.006)	-0.06 (0.005)	1069 (18)			
La14/Wheat	Linear						-0.001 (0.0003)	101.3 (0.35)	0.14
La15/Wheat	Linear	1x					-0.002 (0.0003)	101.3 (0.30)	0.22
		2x					-0.005 (0.001)	104.0 (0.99)	
Sc14/Wheat	Linear						-0.01 (0.002)	114.0 (1.76)	0.45
Sc15/Wheat	Linear						-0.004 (0.001)	103.6 (1.13)	0.13
StA14/Wheat	Linear						-0.02 (0.002)	111.1 (2.18)	0.27
StA15/Faba	Linear						-0.0003 (0.0001)	100.3 (0.06)	0.18
StA15/Wheat	Linear						-0.003 (0.001)	102.7 (0.54)	0.23