EVALUATION OF EFFICACY OF NEW AND EXISTING DESICCANTS IN LENTIL (*LENS CULINARIS* MEDIK)

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ABSTRACT

In western Canada, weeds resistant to acetolactate synthase (ALS) inhibitors have created an extensive challenge for many lentil (*Lens culinaris* L.) producers, particularly producers growing imidazolinone (IMI) resistant lentil. These resistant weed biotypes may not always impact the yield of the current lentil crop, but the resulting seedbank additions and subsequent spread of these resistant biotypes can have a long-lasting impact in successive growing seasons. An effective weed seedbank management program is important to reduce the impact of problem weeds and is vital for farming operations to remain profitable and sustainable in future seasons. This 3-year study at Saskatoon and Scott, Saskatchewan (2012-2014) evaluated the impact of several pre-harvest herbicides on *juncea* canola (*Brassica juncea* L.) and kochia (*Kochia scoparia L.*) dry-down, weed seed production, and the viability and vigour of the weed seeds. The field study examined the effects of different contact herbicides, tank mixed with two different rates of glyphosate (450 g a.i. ha^{-1} and 900 g a.i. ha^{-1}), on weed dry-down, weed seed production and the viability and vigour of developing weed seeds. Five contact herbicides were evaluated: pyraflufen, flumioxazin, saflufenacil, glufosinate, and diquat. Diquat (415 g a.i. g ha^{-1}) and glufosinate (600 g a.i. ha^{-1}) applied alone or tank mixed with glyphosate provided greater dry-down of kochia and *juncea* compared to flumioxazin, pyraflufen, and saflufenacil. No herbicide treatment was able to significantly reduce seed production of either weed species. Although several treatments reduced the thousand seed weight (TSW) of kochia, only a high rate of glyphosate was effective at reducing *juncea* TSW. Growth cabinet studies showed that glyphosate and glufosinate applied alone or in a tank mix together significantly reduced kochia seedling vigour. The number of viable *juncea* seeds was reduced significantly when glyphosate or diquat was applied alone. Overall, glyphosate applied alone was just as effective at reducing seed germination and seedling vigour as tank-mixes with diquat or glufosinate. However, a tank mix of glufosinate and glyphosate as a pre-harvest herbicide treatment in lentil would be the best option to delay the development of glyphosate resistance in kochia and wild mustard. This tank mix would also reduce the viability and vigour of kochia seed additions into the seedbank, as well as provide plant dry-down of lentil and weedy material prior to harvest.

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Table of Contents

LIST OF TABLES

LIST OF ABBREVIATIONS

ACS= Agriculture and Agri-Food Canada Scott Research Farm

ALS= Acetolactate synthase

AMPA= Aminomethylphosphonic Acid

ANOVA= Analysis of variance

AUDPC= Area under the desiccation progress curve

DAA= Days after herbicide application

EPSP= Enolpryuvyl-shukimate phosphate

EG_{50}= 50% germination

ET_{50}= 50% emergence

ET= Economic threshold

GDH= Growing degree days

IMI= Imidazolinone

IPM= Integrated pest management

IWM= Integrated weed management

KCRF= Kernen Crop Research Farm

MOA= Mechanism of action

MRL= Maximum residual limit

NGP= Northern great plains

PHI= Pre-harvest Interval

PPO= Protoporophyrin IX

POST= Post emergence

PRE= Pre-seed/ pre-emergence

TSW= Thousand seed weight

UTC= Untreated check

WSSA= Weed Science Society of America

1.0 Introduction

Lentil (*Lens culinaris* Medik) was first introduced to Saskatchewan growers in 1969, and since then has been readily adopted and grown across the province, particularly in the Brown soil zone (Slinkard and Vandenberg 2014). Saskatchewan is the world's leading exporter of lentil and the centre of Canada's pulse industry, with 90% of Canada's lentil being grown in Saskatchewan (Saskatchewan Pulse Growers 2018). Due to the popularity of lentil crops in Saskatchewan, there has been much research centered on increasing yields, managing weeds developing disease resistance, and reducing lodging (Sarker and Erskine 2006). Weed management in lentil crops is the most important factor in maintaining high yields at harvest (Erman et al. 2008). Yield losses due to weeds varies from 14-100% in pulse crops (Swanton et al. 1993a). Consequently, herbicide research is centered on pre-seed/pre-emergence (PRE) and post-emergence (POST) herbicides that can control the problematic weeds in lentil as it is a poor competitor with weeds.

One of the innovations emanating from this research was the first imidazolinone (IMI) tolerant lentil variety from the University of Saskatchewan's Crop Development Centre (Chant 2004). IMI tolerance was bred into lentil, which allowed Group 2 herbicides (imazamox; imazethapyr, imazamox + imazethapyr) to be sprayed in-crop for weed control (Chant 2004). While this innovation brought many positive advantages for lentil producers, Group 2 herbicide-resistant weeds quickly evolved and still pose a challenge for lentil producers.

Herbicide resistance has become a major challenge for many producers globally. During 2010, economic loss due to weeds in the United States was estimated to be over 2.6 billion dollars (Davis et al. 2003). In western Canada, many lentil producers have great difficulty controlling Group 2 resistant biotypes. Group 2 resistance is the most common form of resistance because of the relatively simple mechanism of action of herbicides within this group. Currently, there are 132 different Group 2 resistant weeds worldwide (Heap 2014). In Canada, there are 20 different Group 2 resistant weeds, the majority which are in the lentil growing regions of Saskatchewan (Heap 2014). According to the Saskatchewan weed survey conducted in 2014 and 2015, both wild mustard (*Sinapis arvensis* L.) and kochia (*Kochia scoparia L.*) are problem weeds and rank 15 and 21st in abundance in Saskatchewan's cereal, pulse and canola acres (Leeson 2016). These two weeds are particularly challenging for lentil growers and can cause extensive yield loss when not adequately controlled. Herbicide resistance in western Canada is not isolated only to Group 2 herbicides. There are a growing number of new cases of herbicide resistance on the prairies, specifically to Groups 1, 4, and 9 (Heap 2017). Therefore, to minimize competition from weeds as well as reduce selection pressure for herbicide resistance, new herbicide mechanisms of action, herbicide tank mixes, improved herbicide rotation, and integrated weed management (IWM) strategies need to be considered.

Herbicide use represents the foundation to controlling weeds in lentil crops. Herbicide application timings are typically before seeding, once the lentil crop has emerged, and pre-harvest. Desiccants are mainly used by lentil growers to dry-down lentil crops and any green weed material. While pre-harvest herbicides in lentil have mainly been used as a crop and weed dry-down, there may be other uses for herbicides at this application timing. For producers looking to reduce the number, or control Group 2 resistant weeds in their fields, or any producer looking to decrease the amount of viable seed or weed seed in the seed bank, the use of these pre-harvest herbicides may provide both in-crop dry-down of escaped and resistant weeds and possible reductions of further weed seed to the seed bank. The use of herbicides as desiccants, particularly glyphosate, has been shown to reduce weed seed germination the following year in many weed species (Bennett and Shaw 2009). Many producers tank-mix herbicides to use as desiccants for enhanced weed control and dry-down of crop biomass. These mixtures of herbicides may have different effects on the germination and vigour of subsequent weed populations. Therefore, it is important to determine which desiccants or mixtures of desiccant will have the greatest impact on weed control and seed bank contributions of problem weeds in the following years.

As Group 2 resistant weeds continue to pose major challenges for Canadian lentil producers, this research is intended to evaluate the efficacy of several desiccants in lentil that can help manage these weeds. The objective of this research was to evaluate the efficacy of desiccants on Group 2 resistant *juncea* and Group 2 resistant kochia in lentil. Results will provide lentil growers with the best herbicide options to help manage wild mustard and kochia in their fields. The results will also shed light on which tank mix options will best reduce weed seed viability of the developing seedlings the following year.

2.0 Literature Review

2.1 Lentil

2.1.1 Lentil History

Lentil (*Lens culinaris* Medik.) is an edible pulse crop from the Leguminosae (Fabaceae) that originated in the Fertile Crescent (Sarker and Erskine 2006). This important western Canadian crop was first grown in Asia around 7,000 BC (Ladizinsky 1979; Bishaw et al. 2007) but is now grown globally where environmental conditions are appropriate (Bahl and Sharma 1993; Muehlbauer and Tullu 1997). Lentil has also become an important nutrition source for many people worldwide, particularly in Asia (Sarker and Erskine 2006). Global production of lentil was approximately 7.6 million tonnes in 2017 (FAOSTAT 2015). Canada is the leading exporting country of lentil with over 3.2 million tonnes produced and exported in 2016 (Government of Canada 2016). In North America, lentil was first cultivated in the cooler, drier regions of the north-eastern United States of America in 1916, and after further development was introduced to western Canada in 1969 (Muehlbauer and McPhee 2002). As a cool season pulse crop, lentil growers have utilized it in their crop rotations for its ability to resist drought and high temperatures. In recent years, North American and Asian countries have played significant roles in lentil production and consumption (Bishaw et al. 2007).

2.1.2 Lentil Morphology

Lentil is a self-pollinated, short, shallow-rooted dicot with an indeterminate growth pattern (Al-Thahabi et al. 1994). The crop is often slow to emerge after seeding and coupled with its short stature and slow early season growth, it is a poor competitor against weeds (Erman et al. 2008). The indeterminate growth means it will continue to grow until unfavorable growing conditions stress the crop into senescence; thus, lentil varieties in Saskatchewan tend only to grow to a height of 30 to 45 cm (Slinkard and Vandenberg 2014). Lentil plants exhibit hypogeal germination, which can help protect the plants in the case of freezing temperatures (Muehlbauer et al. 1985). Temperature, seeding date, and precipitation can greatly affect the number of days until maturity for lentil (Saxena 2009). New nodes are produced every three to five days after germination, with the first true leaf beginning at the third node (McVicar et al. 2017). Flowering begins around the 11-13 node stage, depending on environmental conditions (Slinkard and Vandenberg 2014).

Lentil classification is based on several factors including seed size, seed coat and cotyledon colour, and there can be great variation among cultivars (McNeil et al. 2007; Sandhu and Singh 2007). Lentil is normally divided into two main types; large seeded (macrosperma) Chilean lentil and small to very small seeded (microsperma) Persian, with the former and latter having thousand-seed weights of greater than 60 grams and less than 40 grams, respectively (Muehlbauer et al. 2009; Saskatchewan Ministry of Agriculture 2010). Furthermore, lentil is also classified by seed coat colours including red, green, Spanish brown, and French green (Ghosh et al. 2007; Saxena 2009; Saskatchewan Ministry of Agriculture 2010).

2.1.3 Saskatchewan Lentil Production

In 2016, lentil production in Canada reached a record high at 2.5 million seeded acres. Saskatchewan, which accounted for 90% of the total area of Canadian lentil production, increased the area sown by 40% from the previous year (Statistics Canada 2016b). Lentil is grown primarily in the Brown, Dark Brown, and Black soil zones where the soil and climate are optimal for production (Pulse Canada 2014; McVicar et al. 2017). The remainder of Canada's lentil production is in the southern regions of the provinces of Manitoba and Alberta (Pulse Canada 2018). Lentil is considered a drought tolerant crop with a low tolerance to excessive moisture, salinity, and soils with pH values lower than 5.6 (Mohebbi and Mahler 1989; Slinkard and Vandenberg 2014). In Saskatchewan, lentil is usually seeded from late April to mid-May due to its ability to withstand low temperatures and frost (Saskatchewan Ministry of Agriculture 2010). Average lentil yield varies among types and cultivars, but in Saskatchewan the cumulative average is approximately 1180 kg ha^{-1} (Saskatchewan Ministry of Agriculture 2010).

Since it was first introduced into Saskatchewan in 1969, lentil production has gone through a variety of changes due to plant breeding and agronomic advancements. Slow growing and uncompetitive cultivars have been discarded, while current lentil varieties have been developed to yield more than those first cultivars. Advances in breeding for early maturity and disease resistance have made lentil a more attractive rotation option for producers. In western Canada, particularly Saskatchewan, red lentil has become the dominant class of lentil due to global demand (Saskatchewan Ministry of Agriculture 2010).

2.2 Herbicide Use in Lentil

2.2.1 Competition from Weeds

One of the greatest challenges for lentil plants is competition for resources posed by weeds (Yenish et al. 2009). Due to their short stature and poor early season vigour, weeds compete intensely with lentil for moisture, light, space, and nutrients (Brand et al. 2007). The yield loss in lentil due to weed competition can vary, depending on the species and density of weeds present. For example, yield loss has been reported to range from 44 to 100% (Elkoca et al. 2004; Brand et al. 2007). Weed competition can also affect other aspects of lentil production such as the harvest efficiency or grade and quality of the crop. Weeds that emerge later can reduce harvest efficiency as their immature growth stage and high moisture content can make combining less efficient (Brand et al. 2007). Weed seeds that become mixed with the harvested lentil can elevate dockage and moisture content (Brand et al. 2007; Saskatchewan Pulse Growers 2017).

2.2.2 Weed Control in Lentil with Herbicides

One of the more common methods of controlling weeds in Canada is by using herbicides. Generally, about 90% of cereals, pulses, and oilseeds receive a herbicide application each year (Agriculture and Agri-Food Canada 2012). In the northern Great Plains (NGP) cropping region, herbicides account for 85% of all pesticide applications (Derksen et al. 2002). Other pesticide applications such as fungicides and seed treatments are often dependent on environmental conditions favorable for pest development. Weeds, on the other hand, generally grow every season resulting in yield losses. Therefore, a herbicide application is made every year, regardless of environmental conditions (Swanton et al. 1993a). There are several herbicides commercially available to control monocot weeds in lentil crops, but only a few herbicides to control weeds (Brand et al. 2007). These herbicides are applied to lentil crops generally at three different timings: before the lentil crop has been sown or has emerged (pre-seed or pre-emergence), after the crop has emerged but before flowering (post-emergence), or after the crop has matured, prior to harvest (pre-harvest). Lentil varieties are also divided into two herbicide systems for post-emergent weed control, conventional and imidazolinone-tolerant lentil cultivars, commonly referred to as Clearfield® lentil).

2.2.2.1 Pre-Seed/Pre-Emergent Weed Control

Pre-seed or pre-emergence weed control is done either prior to seeding or just after seeding, but before the crop emerges. Glyphosate, commonly used as a PRE, targets early emerging spring annual weeds, winter annuals, or perennial weeds that have over-wintered from the previous fall or begin to grow prior to the crop emerging. Pre-emergence treatments often have variable efficacy due to environmental factors and little to no residual weed control. Thus, later emerging weeds may grow and compete with the lentil crop (McDonald et al. 2007). While this timing is ideal in cropping systems that practice reduced or conservation tillage, producers must ensure that there are no crop plants emerging during a PRE glyphosate application due to the potential sensitivity of the crop to the glyphosate (Krausz et al. 1996). Apart from glyphosate, other herbicides that are available in Saskatchewan for weed control prior to seeding lentil include saflufenacil (Heat®), carfentrazone (Cleanstart® and Aim®), and MCPA amine (Saskatchewan Ministry of Agriculture 2017). Most of these can be used alone or in combination with glyphosate. According to the Saskatchewan Guide to Crop Protection, lentil producers can also apply ethafluralin and other residual herbicides in the fall (Saskatchewan Ministry of Agriculture 2016).

2.2.2.2 Post-Emergence Weed Control

Post-emergence weed control is carried out after the crop has emerged. The application timing of each herbicide is restricted by the crop stage requirement on the herbicide label to limit any possible damage to the crop (Saskatchewan Ministry of Agriculture 2016). Lentil is one of the herbicide-resistant crops that can be grown in Canada. Imidazolinone tolerant lentil was first released in 2006 (Tan and Bowe 2011), providing producers with several benefits over conventional lentil. Imidazolinone tolerant lentil are non-transgenic and are often selected by producers because of their imidazolinone tolerance. In addition, they have a wider crop staging window for an in-crop IMI herbicide application compared to conventional lentil and a metribuzin application. For example, IMI herbicides can be applied up to 6 nodes compared to applications up to 4 nodes with conventional herbicides like metribuzin (Saskatchewan Ministry of Agriculture 2016). Prior to the development of IMI-tolerant lentil varieties, metribuzin was the only herbicide registered to control broadleaf weeds in-crop (Chant 2004). Imidazoline-based herbicides control a broader spectrum of weeds than metribuzin (Saskatchewan Ministry of Agriculture 2016). The popularity of IMI-tolerant lentil and the nature of the Group 2 mechanism of action has again complicated lentil production in western Canada, largely due to the increase of Group 2 resistance. Group 2 herbicides are widely used in Saskatchewan because of their low use rate, low mammalian toxicity and high efficacy (Devine and Shukla 2000). The wide use of Group 2 herbicides, including in lentil production, has led to the development of Group 2 resistant weed biotypes. This has become an increasing problem for lentil producers because the Group 2 herbicides that were originally used to control problem weeds in lentil, such as kochia and wild mustard, no longer have the efficacy they did when they were first commercialized.

2.3 Herbicide Resistance

According to the Weed Science Society of America (WSSA), herbicide resistance is the inherited ability of a plant to survive and reproduce following exposure to a herbicide dose that is normally lethal to the wild type (WSSA 1998). This ability to resist a mechanism-of-action (MOA) generally develops as either target-site or non-target site resistance (Prather et al. 2000). There are several different mechanisms of resistance that can evolve in plants, which can include altered target site, enhanced metabolism, reduced translocation, altered target enzyme specific activity, sequestration of herbicide away from target site, and reduced entry. Herbicides that have a target site mechanism-of-action act on a specific target site, generally enzymes, where weed control occurs through disrupting biochemical processes (Cobb and Reade 2014). Metabolic resistance is an enhanced ability of a plant to metabolize herbicides through the increased activity of one or more enzymes that naturally can metabolize herbicides (Yu and Powles 2014). Due to the nature of metabolic resistance, in some cases the affected enzymes can confer cross resistance to herbicides that the plant has not encountered (Yu and

Powles 2014). Reduced translocation of herbicides, particularly paraquat and glyphosate has been found in several weeds globally. While the mechanism for reduced translocation is not well understood, reductions of glyphosate translocated to the growing points can significantly reduce the concentration of the herbicide that will inhibit plant growth between resistant and susceptible weeds (Shaner 2009). Altered target enzyme resistance has been discovered in johnsongrass (*Sorgum halepense* L.) where target site was not altered but the target enzyme was 4.5 times less sensitive to applications of clethodim, compared to susceptible biotypes (Burke et al. 2006). Sequestration of a herbicide within a plant has been found in horseweed wherein resistant biotypes are able to sequester high enough concentrations of glyphosate with the plants values where it is then unable to travel to and disrupt the target site. (Ge et al. 2010).

Resistance can develop through a natural mutation in a plant changes the either primary enzyme upon which a herbicide acts or conveys a inheritable trait in the plant that allows it to impede the translocation of the herbicide to the target site. (Vencill et al. 2012). For target site resistance, the interaction between herbicide and the target site will be disrupted and the herbicide may no longer be effective allowing the weed to survive and demonstrate resistance to the applied herbicide (Cobb and Reade 2014). Development of herbicide resistance can be influenced by repeated applications of a single mechanism-of-action, when a plant with a natural mutation and its offspring survive and continue to propagate spreading the resistance mechanism across the field. Other factors that can influence herbicide resistant include the biology of a weed, as well as cropping practices (Beckie 2006). Annual weeds that are highly prolific seed producers and are widely distributed are more likely to develop and spread resistance mutations compared to perennial plants that are less successful at producing high numbers of offspring. Cropping practices can also select for a few dominate weed species that biologically are more susceptible to developing resistance and are repeatably exposed one mechanism of action.

The overuse of herbicides in crops has led to the evolution of herbicide resistant weeds. Globally, there are 487 unique cases of weeds resistant to different mechanisms of action with 253 (147 dicots and 106 monocots) different species having resistance to at least one mechanism of action (Heap 2017). Group 2 herbicides account for a large percentage of herbicide resistance (33%) (Heap 2017). There are approximately 159 different weed species resistant to acetolactate synthase (ALS) inhibitors (Group 2) (Heap 2017). The popularity and repeated use of imidazolinone chemistry, particularly in pea and lentil where the percentage of in-crop use is highest, has led to the development of weeds resistant to Group 2 herbicides (Beckie et al. 2013). Imidazolinones, pyrimidinylthiobenzoates, sulfonylaminocarbonyltriazolinones, sulfonylureas, and triazolopyrimidines are Group 2 herbicide families that all inhibit the production of branched chain amino acids. These herbicides obstruct the development of important enzymes in the creation of the branched-chain amino acids isoleucine (AHAS) or leucine and valine (ALS) (LaRossa and Schloss 1984). Imidazolinone-based herbicides are characterized by their inhibition of the acetolactosynthase enzyme, an enzyme critical in the biosynthesis of several branched-chain amino acids (Whitcomb 1999; Tranel and Wright 2002). These herbicides have high efficacy and control a broad range of grassy and broadleaf weeds (Whitcomb 1999; Tranel and Wright 2002). This class of herbicides is popular due to the low amount of active ingredient required for weed control, low environmental impact, high crop selectivity, soil persistence for residual weed control, and low mammalian toxicity (Devine and Shukla 2000; Tan et al. 2005).

Many of the resistance cases associated with ALS inhibitors are caused by an altered target site. Within native populations, there are eight naturally occurring mutations (Cobb and Reade 2014; Heap 2017). Other herbicides with the target site resistance (include ACCase-inhibitors, mitotic inhibitors and PPO-inhibitors (Powles and Preston 2006). Other types of herbicide resistance are often associated with non-target site resistance, which consists of metabolic resistance, altered translocation, or herbicide sequestering (Prather et al. 2000). Weeds can also be resistant to more than one type of herbicide. Weeds with resistance to multiple herbicides in the same family are known as cross resistant while weeds with resistance to herbicides in different MOA families are multiple resistant (Powles and Preston 1995; Vencill et al. 2012).

There are many factors that influence the evolution of herbicide resistance, including the initial population of herbicide resistant individuals and the intensity of selection by herbicides chemically (Preston and Powles 2002). When herbicides are applied, they create a selection pressure on a weed population, selecting for the members of the population with resistance to the herbicide (Cobb and Reade 2014). These resistant individuals are then able to reproduce. If the same mechanism of action is applied yearly, the percentage of the population with the resistance increases (Cobb and Reade 2014). Cross resistance can also increase if the same family of herbicides, such as ALS inhibitors, are applied too often, even in the case of crop and herbicide rotation, as there is an inadequate amount of time for other herbicide MOAs to control developing ALS resistance

2.4 Problematic Weeds in Lentil Crops

Wild mustard (*Sinapis arvensis* L.) is a prevalent weed found throughout Canada and the north central United States (Christoffers et al. 2006). Considered native to Europe, the Middle East and western Asia, reports of wild mustard populations in western Canada go back as far as 1860 in Fort Garry, Manitoba and 1875 in Dufferin, Manitoba (Mulligan and Bailey 1975). Since then, wild mustard has become an important weed of agricultural crops in the Canadian prairies (Warwick et al. 2005; Friesen et al. 2009). A Saskatchewan weed survey conducted during 2014 and 2015 determined that wild mustard ranked 21st in most abundant weed (Leeson 2016), decreasing from 15th place in 2003 (Leeson et al. 2003).

Wild mustard is a broad-leaved annual weed species with an indeterminate growth habit (Warwick et al. 2000). It is self-incompatible, grows in locations with high light intensity and is readily killed by frost (Warwick et al. 2000). Wild mustard can be easily identified by several of its distinguishing features. This includes kidney-shaped cotyledons, coarsely hairy stems with petiolate lower leaves and sessile upper leaves, bright yellow, four-petalled flowers, pods that are generally hairless and terminated by a flattened beak, and valves that split lengthwise at maturity (Mulligan and Bailey 1975).

Wild mustard is a potentially problematic weed across the Canadian prairies. Due to its high fecundity, competitive growth habit, and persistent seed bank, the yield loss of field crops can be serious. For example, in spring rapeseed, yield can be reduced by 20% with population densities of wild mustard being as low as 10 plants per m^{-2} (Buchanan 2016). Although there are many available herbicides to control wild mustard in field crops, biotypes of wild mustard resistant to Group 2, Group 4, and Group 5 herbicides have been reported in Canada in the 1980s and 1990s (Warwick et al. 2000). ALS inhibitor (Group 2) resistant wild mustard was initially discovered in Manitoba in 1992 (Morrison and Devine 1994) and was later discovered in 2002 in Saskatchewan (Warwick et al. 2005).

Kochia (*Kochia scoparia* (L.) Schrad.) is one of the most prevalent summer annual broadleaf weeds. It is located throughout Canada, except for the Maritime provinces and coastal British Colombia (Royer and Dickinson 2006). Initially categorized as rare in Saskatchewan and Alberta in 1948 (Friesen et al. 2009), kochia was the 15th most prevalent weed across the Saskatchewan in a weed survey conducted in 2014-15 (Leeson et al. 2016). Kochia is present in 15% of surveyed Saskatchewan fields and is most common in lentil (9^{th} in Provincial ranking) occurring in 23% of fields with a mean density of 2.0 plants m^{-2} (Friesen et al. 2009).

Kochia has developed resistance to several mechanisms of action including ALS inhibitors. Group 2 resistant kochia was first discovered in Saskatchewan and Manitoba in 1988 (Morrison and Devine 1994). Due to its tumbleweed dispersal ability as well as being an obligate outcrossing species, populations of Group 2 resistant kochia have become increasingly common. In 2007, Beckie et al. found that 90% of the 109 prairie fields surveyed had widespread resistance to ALS inhibitors (2013). In addition to Group 2 resistant kochia, resistance has also evolved to Group 4 (Synthetic auxins) and Group 9 herbicides (EPSE synthesis inhibitors). Glyphosate resistant kochia (Group 9) was initially discovered in Kansas in 2007, while multiple resistance to both Group 9 and 2 was initially found in southern Alberta in 2012 (Heap 2017). Since then, multiple resistant kochia (Group 9 + 2) has been confirmed in 14 municipalities in Saskatchewan within chemfallow fields, cropped fields (including lentil fields), and uncropped areas (Beckie et al. 2015). Although group 9 + 2 resistant kochia is susceptible to Group 4 herbicides, poor control of kochia with dicamba in the United States was reported in 1994 (Cranston et al. 2001) and resistance to this herbicide has spread ever since (Preston et al. 2009). Although populations of kochia resistant to Group 4 (dicamba, fluroxypyr) in western Canada have not been widely publicized, reports of Group 4 + 2 resistant kochia emerged in the fall of 2015 (Barker 2017). Reports have also stated that triple-resistant kochia was discovered in Alberta (Baerg 2017), although this has not been confirmed. Resistance to three or more mechanisms-of-action in a single weed has already been documented in the United States. In 2013, a corn field in Kansas had confirmed multiple weed resistance to 4 mechanisms of action (Group 2, 4, 5, and 9) (Heap 2017).

This increased spread of resistant kochia may be in part caused by transmission through pollen movement; however, seed dispersal by mature plants moving through the prairie landscape is likely responsible for the long-distance transport (Stallings et al. 1995;

Hall et al. 2014; Beckie et al. 2016). Although the spread of herbicide resistant kochia is difficult to prevent, management practices including crop rotation (Government of Saskatchewan 2017) and rotation of broadleaf herbicides (Government of Manitoba 2015) should be used to delay the development of ALS inhibitors resistance.

2.5 Role of Integrated Weed Management in Managing Herbicide Resistance

With no new herbicide mechanisms of action having been introduced in the last 20 years there has been increasing reliance on existing herbicides. The increase of herbicide resistant weeds (Heap 2016) indicates that current agronomic practices are beginning to fail. Other forms or methods of weed management may become more important if more traditional herbicide chemistries continue to fail to control weeds in crops. Integrated weed management (IWM) is a collection of practices designed to minimize the growth and reproduction of weeds. Examples of IWM tactics include reducing tillage and increasing crop rotations, as well as agronomic practices such as increased seeding rates and cover crops, and mechanical means such as inter-row tillage (Blackshaw et al. 2008; Stanley 2016). However, IWM strategies generally do not address the future impact of weeds and their offspring in a production system.

Other non-herbicide weed seed management approaches include mechanical controls such as swathing, combining, in-field seed destruction, chaff collection, and windrow burning (Walsh and Newman 2007; Walsh and Powles 2007, 2014). These approaches all have different measures of success controlling weeds. They also have different limitations or drawbacks limiting their potential, depending on the weed species, control time, and soil health and environmental consequences. Utilizing just one of these methods may not provide the correct level of control to reduce the weed seed bank, nor will it prevent or stop the spread of herbicide resistant weeds. In lentil, as well as other crops, the use of a desiccant can provide more than simply drying down the crop, especially late in the growing season prior to harvest. These herbicides can also provide annual weed dry-down and control of perennial weeds (Saskatchewan Ministry of Agriculture 2018).

The aforementioned approaches can be used as control options to help reduce weed seed dispersion, population increases, and the spread of herbicide resistance. However, the decision to use any weed management tool should be based on an economic threshold (ET) approach. Yet many decisions focus on the problems that weeds pose immediately, as opposed to the potential long-term impact (Bauer and Mortensen 1992; Norris 1999). In that regard, another approach has been proposed to help address concerns around herbicide resistance.

A zero-seed or zero-tolerance threshold introduced by Norris (1999) and reimagined by Bagavathiannan and Norsworthy (2012) considers the contribution of late season weeds to replenish the seed bank, thereby generating issues into the future. Currently, the critical period of weed control looks to limit crop loss due to weeds and does not consider future implications of later emerging weeds producing offspring (Gallandt 2006). Moreover, economic models used for weed management decisions only consider the cost of the control measure versus the loss of yield if the weeds are not controlled (Zimdahl 2004; Bagavathiannan and Norsworthy 2012). Yet the size of the seed bank and seed fecundity every growing season are critical to the long-term survival or success of weed populations (Davis et al. 2003). A zero-tolerance threshold seeks to minimize these weed seed inputs into the seedbank, thus reducing seedbank populations over the long-term.

The zero-tolerance threshold concept takes a long-term view of weed management, which is important because weed control programs that do not consider future consequences will not help to manage overall weed population growth (Gallandt 2006). This approach is particularly important to consider when contemplating herbicide-resistant weeds. In situations where late weed escapes are not a product of herbicide resistance, they still produce offspring that are added to the seed bank. In theory, those offspring should then be controlled by the next herbicide application they are sensitive to. However, herbicide resistant weeds that escape control of a PRE or POST herbicide application may not be controlled by the next mechanism of action. In this case, they continue to grow and deposit seeds into the seedbank, eventually causing yield losses in subsequent crops. If POST applications fail to control these herbicide resistant weeds, then the next herbicide timing that can prevent the weeds from producing offspring are pre-harvest applications (Bagavathiannan and Norsworthy 2012). Pre-harvest applications can serve to minimize weed seed contributions to the seedbank by arresting seed development, which may render some weed seeds non-viable.

2.6 Pre-Harvest Herbicides

Herbicides are used as desiccants to reduce seed moisture, improve quality, and increase harvest efficiency by controlling weeds that can interfere with harvest (Yenish and Young 2000). Pre-harvest herbicides are typically used in lentil after the crop is mature and when the seed colour is changing. Desiccation is particularly important in lentil as its indeterminate growth pattern can result in higher percentages of immature green seeds, thus reducing quality (Saskatchewan Ministry of Agriculture 2016). Different herbicides need to be applied at different stages of maturity, based on seed colour change (Saskatchewan Ministry of Agriculture 2016). These herbicides are used to reduce the time until harvest, thereby reducing the risk of damage from inclement weather (Tang et al. 1992).

Pre-harvest herbicides can be classified as either true desiccants or harvest aids, as well as by their activity (contact or systemic.) True desiccants are used to rapidly dry-down plants. These desiccants are often contact-based, though not all contact herbicides are true desiccants (Ware and Whitacre 2004; Schemenauer 2011). Contact herbicides tend to have little or no systemic activity within the plant. Harvest aids consist of herbicides with systemic qualities or contact herbicides with slower mechanisms of action and some limited systemic properties. Systemic herbicides are absorbed by the plant and are translocated to other parts of the plant (Baumann et al. 2008).

Several desiccants and harvest aids are actively used in Canada for a variety of crops, including diquat, glufosinate, saflufenacil, pyraflufen, flumioxazin, and glyphosate. In western Canada, diquat (group 22) is registered in lentil as a true desiccant under the trade name Reglone®(Saskatchewan Ministry of Agriculture 2016). As a true non-selective herbicide and desiccant, diquat is very effective as a crop dry-down herbicide (Zagonel 2005; Cobb and Reade 2014; Saskatchewan Ministry of Agriculture 2016). Diquat generally does not affect the seed, as its rapid necrosis of tissues impedes translocation, limiting its systemic properties (Zagonel 2005; Saskatchewan Ministry of Agriculture 2016). Diquat does not have any crop restrictions with regard to following crops, and it has strong soil binding properties to negatively charged colloids (Cobb and Reade 2014; Saskatchewan Ministry of Agriculture 2016). As a contact herbicide, it is important to ensure good coverage for maximum efficacy (Zagonel 2005; Saskatchewan Ministry of Agriculture 2016). The mechanism of action of diquat inhibits photosynthesis by diverting electrons in Photosystem I and forming hydroxyl radicals that disrupt cell membranes and block protein and lipid synthesis (Cobb and Reade 2014). This production of peroxide radicles destroys the integrity of cell membranes, resulting in rapid tissue dry-down and plant death (Black and Myers 1966). The pre-harvest interval (PHI) in lentil is 4 to 7 days after application (Saskatchewan Ministry of Agriculture 2016).

Glufosinate is registered in western Canada as a desiccant under the trade name Good Harvest® (Fleury 2015; Saskatchewan Ministry of Agriculture 2016). In western Canada, it is more commonly known as the post-emergence herbicide Liberty®, for in-crop use in Invigor® canola varieties. Glufosinate is a non-selective herbicide with limited translocation properties. As a Group 10 product, it works by inhibiting glutamine synthesis, reducing the conversion of glutamate and ammonium into glutamine, ultimately reducing photosynthesis. This leads to a depletion of the amino acids glutamine and glutamate, as well as other important plant acids and enzymes that lead to plant death (Hall et al. 1999; Cobb and Reade 2014). Like diquat, glufosinate has no soil activity, though for glufosinate it is due to a rapid breakdown of the herbicide in the soil. High carrier volume is important to ensure adequate coverage across the plant, which is typical of contact herbicides (Saskatchewan Ministry of Agriculture 2016). For lentil desiccation, glufosinate (as Good Harvest®) is applied when 40 to 60% of pods turn yellow or brown (Saskatchewan Ministry of Agriculture 2017).

Saflufenacil is now registered in western Canada as a harvest aid for red lentil varieties under the trade name Heat LQ® (Saskatchewan Ministry of Agriculture 2017). Saflufenacil is a Group 14 herbicide that inhibits the protoporphyrinogen IX oxidase (PPO) enzyme, which converts protoporphyrinogen IX to protoporophyrin IX (Grossmann et al. 2010; Soltani et al. 2010). This prevents the biosynthesis of chlorophyll and causes cell membranes to deteriorate (Dayan et al. 2010; Grossmann et al. 2010). As a harvest aid, the (PHI) is 3 days, between the herbicide application and combining, and the application timing for saflufenacil is when 15% of the bottom pods are brown and rattle when shaken (Saskatchewan Ministry of Agriculture 2016). Saflufenacil has both contact and systemic properties, which makes it a versatile herbicide. It is interesting to note that saflufenacil is unique in that it has some mobility in both the xylem and phloem, unlike other PPO inhibiting herbicides with systemic activity only through the xylem (Ashigh and Hall 2010; Soltani et al. 2010). While there is some ability of glyphosate to translocate due to its delayed degradation of vascular tissues, it is thought that the degradation still occurs too quickly to allow for complete translocation throughout larger plants and ideal applications should be targeted to plants less then 10cm tall (Grossmann et al. 2011). This limited translocation may impact saflufenacil ability to provide complete dry-down of the large weeds and crop at the pre-harvest application timing.

Flumioxazin and pyraflufen-ethyl are also Group 14 herbicides used throughout Canada (Saskatchewan Ministry of Agriculture 2016). Flumioxazin is registered under the commercial name Valtera® and Chateau®. It is used for pre-seed or pre-emergence applications in several crops (soybean (*Glycine max*), field pea (*Pisum sativum* L), spring wheat (*Triticum aestivum* L), and potato (*Solanum tuberosum* L)). It is also registered as a fall application prior to the spring seeding of soybean, field pea, lentil, and spring wheat (Valent Canada Inc. 2009; Soltani et al. 2013; Saskatchewan Ministry of Agriculture 2016). Pyraflufen-ethyl is also used as a desiccant for cotton and potato (Nichino Europe Co. Limited 2012). While neither flumioxazin nor pyraflufen are currently registered in lentil as a desiccant or harvest aid in Canada, they are registered in other crops and could also have a place in lentil in the future.

Glyphosate is registered in lentil as a harvest aid (Saskatchewan Ministry of Agriculture 2016). The mechanism of action of glyphosate is the inhibition of enolpryruvyl-shikimate phosphate (EPSP) synthase, which is an enzyme used to produce amino acids in the shikimate pathway (Ashigh and Hall 2010; Cobb and Reade 2014). Final plant death occurs due to the inhibition of photosynthesis, as the plant cannot create proteins stemming from the buildup of shikimate-3-phosphate (Franz et al. 1997; Duke and Powles 2008). As a non-selective, systemic herbicide, glyphosate can translocate throughout the plant phloem and xylem and slowly inhibit plant growth (Cobb and Reade 2014; Saskatchewan Ministry of Agriculture 2016). Glyphosate has no contact properties and does not have any residual soil properties that would affect the germination or growth of rotational crops (Saskatchewan Ministry of Agriculture 2016). Glyphosate and its metabolite (AMPA) have been found to persist in the soil, although there was little risk of crop damage from soil residues in wheat, field pea, and canola (Blackshaw and Harker 2016). The systemic action of glyphosate means that application timing is important. Harvest aid applications made too early can have a negative effect on seed quality as chemical residues can accumulate in the seed. Consequently, glyphosate is not registered as a harvest aid for any crop grown for seed (Wilson and Smith

2002; Saskatchewan Ministry of Agriculture 2016). Glyphosate is typically applied to lentil when the lower 35% of the pods have turned brown (Schemenauer 2011; Saskatchewan Ministry of Agriculture 2014).

Although pre-harvest application of glyphosate can be used as a harvest management tool to help dry-down the lentil, its effects are slow and require more time to inhibit plant growth than other harvest aids (Government of Alberta 2017). A major advantage with using a pre-harvest application of glyphosate is improved control of perennial weeds (Menalled 2010; Soltani et al. 2013; Hill et al. 2016). Pre-harvest applications represent the ideal time to control perennial weeds such as Canada thistle, sow thistle, and quack grass (McVicar et al. 2017). At pre-harvest, perennial weeds have begun putting energy reserves into their root systems for overwintering (Government of Alberta 2017). Since glyphosate is a systemic herbicide, it has the ability to move throughout the plant and into the roots, thus providing control of perennial weeds (Government of Alberta 2017). This increases the efficacy of weed control compared to spring applications of glyphosate, which simply results in injury to the top growth of the weed (Fleury 2015).

2.6.1 Harvest Aid Considerations

Choosing the correct pre-harvest herbicide depends on the grower's specific needs or most vital concern (Menalled 2010). Systemic herbicides like glyphosate provide great weed control on all weeds with poor crop dry down, while contact herbicides provide greater crop dry down but reduced weed control (Menalled 2010). A lentil producer needs to decide which need, crop dry down or weed control, is more important as that may have an impact on the chosen pre-harvest herbicide and its application timing. Regardless of the rationale behind applying a pre-harvest herbicide, there are several considerations to take prior to application. Examples of these include the correct herbicide, application timing, and crop destination.

Herbicide timing is important, as an incorrect timing of application can reduce crop yield and quality (Fleury 2015). The effect of herbicide timing on yield has been studied in many crops, including soybean, dry edible bean (*Phaseolus vulgaris* L.), and lentil. Glyphosate application in dry bean prior to 75% maturity leads to reduced dry bean seed weight, which indicates that applying glyphosate too early may affect seed quality

(McNaughton et al. 2015). In soybean, harvest application prior to the R7 stage had the potential to negatively affect yield and seed weight (Bennett and Shaw 2000a). Harvest aid application in lentil prior to 50% seed moisture content had a negative impact on yield (Zhang et al. 2017).

Harvest aid application timing can also impact the end use of the seed, such as for export to another country or for on-farm use as seed by growers. Moreover, every pre-harvest herbicide has different restrictions on what can be done with the crop after harvest. For example, glyphosate cannot be used in lentil that is grown for seed production due to its systemic ability to move into the seed and reduce the quality, viability, and vigour of the seed (Baig et al. 2003). In Saskatchewan, it is not recommended to use glyphosate as a harvest aid in any crop that is grown for seed production (Saskatchewan Ministry of Agriculture 2014).

The destination of the crop is very important when making pre-harvest herbicide decisions. If the lentil crop is grown for human consumption, then the export destination of the crop is another important consideration. Different countries have different restrictions on which herbicides can be used as desiccants in each crop and apart from herbicide restrictions, the maximum residue limit (MRL) of each herbicide in the seed can be different depending on the country and end use of the product (Table 2.1). This is especially important to Canadian pulse growers as more than 85% of Canada's pulses are marketed and exported out of the country (Pulse Canada 2018).

For lentil producers in Saskatchewan, understanding the correct application timing for each herbicide is important to ensure that they will not damage the crop seed, the grain will be marketable, and the crop can be used for its intended purpose. In lentil, an application at the incorrect timing of less than 30% seed moisture can lead to high seed residue and cause a shipment to be rejected (Zhang 2016). Similar results were found in dry bean desiccation where glyphosate applications, applied pre-harvest before 75% maturity, could cause unacceptable residues in the seed (McNaughton et al. 2015).

The use of the correct herbicide as a desiccant or harvest aid is also an important consideration. As previously mentioned, glyphosate is an important herbicide globally and to reduce the risk of further herbicide resistance, tank-mixing with a different but equally effective mechanism-of-action can be beneficial. Apart from managing herbicide resistance, the use of tank mixes can result in greater crop dry-down and more reduced chemical residue in the seed. Zhang et al. (2016) reported that the addition of diquat and glufosinate increased the effectiveness of the dry-down in lentil. This tank-mix also ensured that glyphosate residue levels were at acceptable levels for many of Canada's lentil markets.

The practice of applying pre-harvest herbicides to dry down green weeds leads to the opportunity to reduce the viability of weed seed production (Bennett and Shaw 2000b). Sometimes referred to as crop-topping in Australia, the late season application of nonselective herbicides, including glyphosate, has often been studied to reduce the seed production of several weeds (Walsh and Powles 2007). Pre-harvest desiccants, including glyphosate + sodium chlorate, glufosinate, and oxyfluorfen were found to reduce the germination of *Senna obtusifolia* in *Glycine max* (Bennett and Shaw 2000b). In a study conducted by Johnson and Norsworthy (2014), the viable seed production of Johnsongrass (*Sorghum halepense)* was reduced by 97% when glyphosate and clethodim were applied at the boot stage. Additionally, Shuma et al. (1995) found that the application of glyphosate to *Avena fatua* L. at anthesis completely eliminated the production of any viable seeds.

Table 2.1 Herbicide Active Ingredient Maximum Residue Limits (MRL) for several counties in parts per million (ppm). Sourced from Global MRL Database (2017).

	Current MRLs				
Active Ingredient	Canada	Europe Union	Japan	United States	Codex
			ppm		
Diquat	0.20	0.02	0.20	0.05	0.20
Flumioxazin	0.07	0.02	0.07	0.07	0.07
Glufosinate	N/A	N/A	N/A	N/A	N/A
Glyphosate	4.00	10.00	2.00	8.00	5.00
Pyraflufen	N/A	N/A	N/A	N/A	N/A
Saflufenacil	0.30	0.03	0.30	0.30	0.30

For this practice to be beneficial, it is required that the weed seeds be immature despite crop maturity, to allow for the non-selective herbicide to target the weeds without causing damage to the crop and risking significant yield loss (Walsh and Powles 2007). For example, seed-set reductions can be reduced in rigid rye grass when the pre-harvest application is delayed and the weeds and developing seeds become more mature (Walsh and Powles 2007). The control of seed viability in weeds and crops with indeterminate growth tend to be lower due to the extended period of reproduction (Bagavathiannan and Norsworthy 2012).

3.0 Evaluating the efficacy of harvest aids in lentil for late-season control of kochia (*Kochia scoparia* L.) and Xceed® canola (*Brasicca juncea* L.)

3.1 Introduction

Lentil (*Lens culinaris* Medik.) has become an important crop in western Canada since its introduction in 1969 (Muehlbauer and McPhee 2002). In addition to providing high economic return and export value, lentil crops help to lengthen crop rotations on the prairies. Furthermore, lentil can fix its own nitrogen when inoculated with the proper *Rhizobium* species, which reduces fertilizer costs and requirements (Saskatchewan Pulse Growers 2018). The most significant threat to lentil production is weed competition, which can cause yield and quality loss, as well as reduced harvest efficiency (Boerboom and Young 1995; Erman 2004). Control of broadleaved weeds is a significant problem in lentil production and has resulted in the popular use of imidazolinone (IMI)-tolerant lentil (Chant 2004). Consequently, imidazolinone herbicides have been overused, resulting in Group 2 resistance in several weed species (Heap 2016). With in-crop herbicides failing to control weeds in IMI-tolerant lentil, producers need other control options. Failure of in-crop herbicides to control weeds can result in high densities of mature weeds at harvest, which can interfere with harvest operations and contribute seeds to the weed seed bank (Norsworthy et al. 2014). The only other in-season chemical control options are pre-plant and pre-harvest herbicides.

Wild mustard (*Sinapis arvensis* L.) and kochia (*Kochia scoparia* L.) are two pernicious weeds in lentil. Ninety percent of kochia populations and a large population of wild mustard in western Canada are resistant to Group 2 ALS-inhibiting herbicides, causing difficulty for in-crop control in IMI-tolerant lentil (Beckie et al. 2013). The failure to control these weeds with in-crop herbicides results in the need for other chemical control options. Two examples of other options include desiccants that rapidly dry down plant material, and harvest aids that gradually dry down plant material.

Controlling weed seed production is an important component of weed management systems. Reducing the amount of viable weed seed returned to the seed bank can impact the intensity of competition from weed populations in future years (Walsh et al. 2013). Using pre-harvest herbicides as desiccants and harvest aids can be used for more than just crop dry-down and the desiccation of green weed material in the crop. Several studies have investigated the effects of pre-harvest herbicides on problem weeds in different crops, such as glyphosate resistant palmar amaranth (*Amaranthus palmeri* L.) and annual ryegrass (*Lolium rigidum* L.) (Boutsalis et al. 2012; Norsworthy et al. 2016). These studies have found that herbicides applied pre-harvest, combined with other forms of integrated pest management such as cultural and mechanical mechanisms, are an important tool for reducing the spread and impact of some problem weeds. These herbicides can reduce the spread of problem weeds by either killing plants before they set seed or reducing the number of viable seeds produced.

To be effective, crop desiccation must occur prior to the time that plants are physiologically mature and when they are allocating resources to seed development. This may or may not coincide with the optimum timing to reduce weed seed production, depending on the crop and weed species present. As a result, applying desiccants prior to physiological maturity of the crop may result in unacceptable herbicide residues in the harvested seed (Zhang et al. 2017). Saflufenacil and diquat are two common desiccants available for use in western Canada. As well, glyphosate remains a popular harvest aid due to its ease of use, efficacy, and low price (Saskatchewan Ministry of Agriculture 2014). However, there are significant factors that may limit the use of glyphosate in the future. The evolution of glyphosate resistant weeds is a significant threat to crop production in western Canada. Glyphosate is registered for use pre-seed, pre-harvest, and post-harvest in a number of crops (Saskatchewan Ministry of Agriculture 2018). This use pattern, combined with the use of glyphosate in genetically modified crops (GMO) such as corn, soybean, and canola has led to concerns about further development of glyphosate resistant weeds. It is possible the increase in glyphosate resistant weeds could preclude the use of glyphosate on several weeds, including kochia and wild mustard (Heap 2017; Saskatchewan Ministry of Agriculture 2018). Other factors that could limit the use of glyphosate as a pre-harvest herbicide are glyphosate residues in crop seed and food, as well as glyphosate being recently declared a ‘probable’ carcinogen (Tarazona et al. 2017; World Health Organization 2016). While glyphosate maximum residue levels (MRLs) allowed in food are regulated by each country, recently there has been public concern in North America over whether current glyphosate residue levels are adequate to prevent over-exposure of people to glyphosate.

As an indeterminate plant, lentil can continue to grow into late fall and thus requires harvest aid treatments to assist in plant dry-down, to avoid harvest losses, and to improve harvest efficiency (McVicar et al. 2017). While a pre-harvest herbicide will need to be applied in-crop for successful lentil production, further research is needed to determine the effectiveness of these herbicides on problem weeds in lentil, particularly kochia and wild mustard. The objective of this study was to determine the efficacy of glyphosate, pyraflufen, glufosinate, flumioxazin, saflufenacil, and diquat applied pre-harvest on the dry-down and seed production of kochia and *juncea*. These herbicides were chosen because either they already have an established use pattern in lentil (glyphosate, saflufenacil, diquat) or they are used as pre-harvest herbicides in other crops (pyraflufen in potatoes; flumioxazin in dry beans) (Ivany, 2005; Saskatchewan Ministry of Agriculture 2016; Soltani et al. 2013; McNaughton et al. 2015).

3.2 Hypothesis

Tank-mixing of glyphosate at a rate of 900 g a.e. ha^{-1} rate with the contact herbicides in this study will provide greater dry-down of weed biomass and reduce weed seed production compared to either glyphosate applied alone, or the contact herbicides applied alone.

3.3 Material and Methods

3.3.1 Site Description

Field experiments were conducted in 2012, 2013, and 2014 near Saskatoon, Saskatchewan at the Kernen Crop Research Farm (52°16’ N, 106°51’ W) and at Agriculture and Agri-Food Canada Scott Research Farm (52°36’ N, 108°84’ W), near Scott, Saskatchewan. The Kernen site is located on a Sutherland series clay loam (Bradwell Dark Brown Chernozem; 10% sand, 40% silt, 50% clay) with a pH of 7.4 and 3.8% organic matter. The Scott site is on a loam soil (Dark Brown Chernozem; 38% sand, 40% silt, 21% clay) with a soil pH of 6.3 and 2.4% organic matter.

3.3.2 Experimental Design and Procedures

The experiment was designed as an 18-treatment randomized complete block design with four replicates. Plot size at Saskatoon and Scott was 2 m wide x 6 m long and 2 m wide x 5 m long, respectively. Glyphosate (900 g ae ha^{-1}) was applied prior to seeding to control any emerged weeds. CDC Maxim lentil was seeded in this study because it is a commonly grown IMI-tolerant cultivar. All seed was sourced from a pedigreed seed grower. Prior to seeding, all lentil seed was treated with Apron Maxx RTA (0.73% fludioxonil: 1.10% metalaxyl-M and S-isomer) applied at a rate of 325 mL 100 kg^{-1} of seed. The seed was inoculated using Liquid Nodulator® inoculant (*Rhizobium leguminosarum* biovar *viceae*) at a rate of 2.76 mL kg^{-1} in 2012. In all other site-years, Tag Team® Granular (*Rhizobium leguminosarum* and *Penicillium bilaii*) was applied in the seed row at a rate of 2.8 kg ha^{-1}.

Lentil was seeded at a rate of 130 plants m^{-2} at a depth of 3 cm and on 22 cm rows using a small plot drill equipped with single shoot hoe openers at both Saskatoon and Scott. IMI-resistant *Brassica juncea* L. was then seeded perpendicular to the crop at 2 cm deep with the same plot seeder at a target density of 30 plants per m^{-2}. IMI-resistant *B. juncea* was used as a pseudo-weed in place of wild mustard as wild mustard typically does not have high germination relative to *B. juncea*. A possible concern with utilizing a domesticated crop in place of a weed in this study could be seed shatter at the time of harvest, where a crop would retain the seed and the weed would not be shatter resistant. A study evaluating the seed shed of several weeds found that wild mustard seed shed at the time of harvest was less than 2% in wild mustard (Burton 2016). Low seed shatter in wild mustard at harvest suggest that most of the seed is retained by the plant just as it is in a *B. juncea* crop. While observations in this study are for *B. juncea* it was decided that using *B. juncea* as a surrogate for wild mustard was appropriate. ALS-resistant kochia was then broadcast across the trial at a rate of 30 seeds m^{-2} using a pneumatic spreader. The entire trial was rolled with a small plot roller to improve soil to seed contact, promote kochia germination, and to level the soil for harvest operations. By seeding both IMI-resistant B. *juncea* and ALS-resistant kochia, a relatively pure stand of herbicide resistant weeds was established following a post-emergence application of imidazolinone herbicides.

Herbicide and fungicide maintenance applications were made in all site-years. Imazamox + imazethapyr (30 g a.i. ha^{-1}) was applied between the 5th and 6th node stage of lentil development at both sites. At Scott, clethodim (88 g a.i ha^{-1}) was tank-mixed with imazamox + imazethapyr to improve grassy weed control. For disease management, prothioconazole (166 g a.i. ha^{-1}) was applied at Saskatoon while boscalid (294 g a.i. ha^{-1}) was applied at Scott when lentil reached the early flowering stage (20-50% flowering).

3.3.3 Treatments

Treatments consisted of five herbicides applied alone and tank-mixed with two different rates of glyphosate, with an untreated control included as a check. These treatments consisted of flumioxazin, saflufenacil, pyraflufen-ethyl, glufosinate, diquat, and glyphosate (Table 3.1). The treatments were applied to foliage at the recommended lentil seed moisture content of approximately 30% (Saskatchewan Ministry of Agriculture 2014). The herbicide rates were determined by label recommendations taken from the Saskatchewan Crop Protection Guide (Saskatchewan Ministry of Agriculture 2014), with glyphosate applied at both the full (900 g a.e. ha^{-1}) and half the registered rate (450 g a.e. ha^{-1}).

Harvest aids were applied with the recommended adjuvants, Merge® (50% surfactant; 50% petroleum hydrocarbons solvent) or Agral 90® (90% nonylphenoxy polyethoxy ethanol). All treatments were applied in a carrier volume of 200 L ha^{-1}. At Saskatoon, all treatments were applied using an air-pressurized tractor mounted sprayer equipped with shielding (110-015 AirMix nozzles, 275 kpa, 45 cm spacing). A CO_2-pressurized bicycle sprayer (110-003 AirMix nozzles, 276 kpa, 25 cm spacing) was used at Scott. Environmental conditions during treatment application at each site-year can be found in Table 3.2.

3.3.4 Data Collection

Lentil plant density was measured two weeks after emergence by counting the number of emerged plants in two, one-meter rows in each plot. Weed counts were also preformed counting the numbers of both kochia and *juncea* in two randomly selected one square foot spots per plot. Visual desiccation ratings of the dry-down of each weed species were conducted at 0, 7-10, 14-21, and 28 days after herbicide application (DAA) based on the Canadian Weed Science Society visual rating scale. The scale considers 80% as commercially acceptable weed control and 70 to 80% as commercially acceptable suppression (Vanhala et al. 2004). The area under the desiccation progress curve (AUDPC) was calculated using the visual ratings as the following equation:

$$AUDPC = \left(\frac{D_1 + D_2}{2}\right)(t_2 - t_1) + \left(\frac{D_2 + D_3}{2}\right)(t_3 - t_2) + (\frac{D_3 + D_4}{2})(t_4 - t_3)$$

where D_n represent the observed desiccation rating at each evaluation and t_n represent the number of days after the herbicide application.

The crop was harvested with a small plot combine when the lentil crop was at harvest maturity. Harvested seeds were weighed and then oven-dried for 48 hours to determine seed moisture content. Thousand-seed weight (TSW) was measured by counting and weighing 250 seeds and multiplying by four. Straw moisture content was measured immediately after threshing each plot by collecting a sample of plot biomass from the straw deposited by the combine (lentil and weeds combined) and drying in an oven at 80^{o}C for 48 hours.

3.3.5 Statistical Analysis

All data were analyzed using the MIXED Procedure in SAS 9.3 (SAS Inst. 2014). PROC UNIVARIATE and Levene's test were used to examine the assumptions of normality and homogeneity of variance of the residuals. Heterogeneous variances were modeled when necessary using the REPEATED command in PROC MIXED. Where residuals did not conform to the assumptions of ANOVA, transformations were used.

In the mixed model, herbicide treatments were treated as fixed effects with site-years, replications (nested in site-years) and site-year by treatment interactions initially considered random effects. The COVTEST option was used to determine if there were significant interactions between the fix and random factors in this study (SAS Inst. 2014). Where there were significant interactions between site-years and herbicide treatment it was decided to analyze site-years individually. Tukey's HSD was used to separate means when treatment differences were significantly different at $P \leq 0.05$. The PDMIX800 macro was used for letter grouping when separating treatment means in SAS (Saxton 1998). Specific comparisons of interest were made between various herbicide treatments using single degree of freedom contracts

Table 3.1 Herbicide treatments and application rates for each herbicide treatment evaluated at Saskatoon and Scott, Saskatchewan, Canada from 2012 to 2014.

Herbicide	Rate (g a.e. ha^{-1}/g a.i. ha^{-1})
Untreated	0
Glyphosate	450
Glyphosate	900
Pyraflufen-ethyl‡	20
Pyraflufen-ethyl + Glyphosate‡	20 + 450
Pyraflufen-ethyl + Glyphosate‡	20 + 900
Glufosinate	600
Glufosinate + Glyphosate	600 + 450
Glufosinate + Glyphosate	600 + 900
Flumioxazin¶	210
Flumioxazin + Glyphosate¶	210 + 450
Flumioxazin + Glyphosate¶	210 + 900
Saflufenacil§	50
Saflufenacil + Glyphosate†	36 + 450
Saflufenacil + Glyphosate†	36 + 900
Diquat¶¶	415
Diquat +Glyphosate¶¶	415 + 450
Diquat +Glyphosate¶¶	415 + 900

‡ Merge® at 1% v/v was added in pyraflufen-ethyl and the tank mixture of pyraflufen-ethyl+glyphosate treatment.

¶ Agral 90® at 0.25% v/v was added in flumioxazin treatment and the tank mixture of flumioxazin+glyphosate treatment.

§ Merge® at 1 L ha^{-1} was added in saflufenacil treatment.

† Merge® at 0.5 L ha^{-1} was added in the tank mixture of saflufenacil+glyphosate treatment.

¶¶ Agral 90® at 0.1% v/v was added in diquat and the tank mixture of diquat+glyphosate treatment

Table 3.2 Dates of application timings and environmental conditions for each treatment at Saskatoon and Scott, Saskatchewan, Canada from 2012 to 2014.

Site	Year	Application timing	Application date	Air Temperature (°C)	Relative humidity (%)
Saskatoon	2012	30%	28-Aug	26.0	42.7
	2013	30%	19-Aug	26.3	45.3
	2014	30%	19-Aug	23.0	47.0
Scott	2013	30%	04-Sep	16.3	62.9
	2014	30%	28-Aug	14.7	83.8

3.4 Results and Discussion

3.4.1 Kochia and *B. juncea* Dry-Down

It was decided to analyze data within site-year to explore the significant interaction between site-year and treatment in more detail (Table 3.3). Kochia dry-down was significantly affected by treatment in all site-years excluding Scott 2013 (Table 3.4). Treatments containing diquat and glufosinate resulted in the highest AUDPC values at Saskatoon and Scott in 2014. Contact treatments containing saflufenacil, pyraflufen or flumioxazin did not provide the same level of dry-down compared to diquat and glufosinate. This indicates greater overall desiccation achieved with diquat and glufosinate in comparison to saflufenacil, pyraflufen, flumioxazin, and the untreated check. At Saskatoon in 2012, the AUDPC values for glufosinate (423%) and diquat (318%) were the greatest compared to the untreated check. The PPO herbicides saflufenacil, flumioxazin, and pyraflufen provided 145%, 115%, and 131% greater dry down respectively compared to the untreated check. Tank-mixing the high rate of glyphosate with flumioxazin or saflufenacil increased the AUDPC by 49% and 37%, compared to the respective herbicides applied alone. At the remaining Saskatoon site-years (2013, 2014), treatments containing glufosinate or diquat resulted in increased dry-down as the AUDPC values were more than two times that of the untreated check (AUDPC values of 599 and 610 for the untreated check respectively). Adding glyphosate to glufosinate or diquat did not improve AUDPC values in these site-years compared to glufosinate or diquat alone.

Table 3.3 P-values derived from analysis of variance showing fixed factor combinations at Saskatoon and Scott, Saskatchewan in 2012-2014.

Source	Kochia AUDPC	*B. juncea* AUDPC
Site-year	0.1629	0.1788
Herbicide	0.0263*	0.0155*
(Site-year) (Herbicide)	<.0001***	<.0001***

*, **, ***, significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

Pre-planned comparisons showed that the addition of the contact herbicides to glyphosate resulted in a significant improvement in visual kochia dry-down at Saskatoon compared to glyphosate alone. While there were no significant differences between the pre-planned contracts at Scott in either year, there were significant treatment differences in the 2014 Scott site-year (Table 3.4). At Scott in 2014, glyphosate at a full rate and both treatments containing diquat and glufosinate alone provided kochia dry-down, with AUDPC values at 8%, 39% and 48% percent higher than the untreated check. The addition of either rate of glyphosate to both glufosinate or diquat did not have a further effect on the AUPDC compared to the two herbicides applied alone.

Juncea AUDPC results were similar to those of kochia across all site-years (Table 3.5). In the three Saskatoon site-years, diquat and glufosinate treatments provided the greatest overall desiccation (highest AUDPC values) in comparison to all other treatments. In contrast, there were no significant differences between the treatments at Scott in 2013, while results in 2014 were similar to those at Saskatoon in that diquat and glufosinate provided the greatest visual dry-down. In most of the site-years, orthogonal contrasts showed a significant benefit to adding a contact herbicide to glyphosate compared to applying glyphosate alone, with the exception of Saskatoon 2012 and Scott 2013 (Table 3.5). For *juncea*, contrasts indicated that with the exception of Saskatoon 2012, there was no benefit to increasing the rate of glyphosate from a half (450 g a.e. ha^{-1}) to a full rate (900 g a.e. ha^{-1}) when tank-mixing with a contact herbicide.

The results of the desiccation ratings indicate that while there were significant benefits to using pre-harvest herbicides to dry-down kochia and *juncea*, results were variable. This was most likely due to environmental conditions such as precipitation, light, temperature, relative humidity and wind. Changes in these abiotic factors can influence how rapidly a plant matures, which can in turn affect how quickly herbicides can enter a plant and travel to the target site (Varanasi 2016). Overall, both diquat and glufosinate applied alone or tank mixed with glyphosate provided the most consistent dry-down of *juncea* and kochia across all site-years. These findings are consistent with Soltani et al. (2013), where the addition of a contact herbicide to glyphosate increased visual dry-down of several weed species in dry bean (*Phaseolus vulgaris* L.). The authors also reported little to no increase in the visual dry-down of these weeds when glyphosate was added to the contact herbicides, suggesting that a contact herbicide alone was sufficient. This is also in agreement with Ellis et al. (1998) and Bennett and Shaw (2000b) who reported that glufosinate provided consistent desiccation of pitted morning glory (*Ipomoea lacunose* L.) and spotted spurge (*Euphorbia maculata* L.) in dry bean. Zhang et al. (2016) reported that both glufosinate and diquat provided the most consistent dry-down of lentil.

While diquat and glufosinate provided the most consistent desiccation, the effect of other contact herbicides and glyphosate were inconsistent across site-years. Glyphosate is a systemic herbicide with slow translocation, which would explain the lower AUDPC values that we observed compared to glufosinate and diquat. The reduced efficacy of saflufenacil, pyraflufen, and flumioxazin may be explained by their mechanism of action, as these herbicides inhibit protoporphyrinogen oxidase (PPO).

Because of this, weed stage and size can be important factors that impact efficacy since most PPO herbicides are contact herbicides and have limited xylem and phloem mobility within the plant (Grossmann et al. 2010). PPO herbicides are not as mobile as glyphosate because they break down the protein lipid membranes in plants, which causes plant cells to desiccate and rapidly breakdown, limiting translocation (Grossmann et al. 2010; Soltani et al. 2010). With the contact-like nature of PPO herbicides, water volume is also important because these herbicides do not translocate very well and generally only inhibit plant processes in the immediate area they contact (Cobb and Reade 2014). This may be one of the reasons that these herbicides often have superior efficacy on smaller weeds than larger weeds. Smaller weeds have less surface area and tend to be more susceptible to a herbicide application. Each point of herbicide contact on a smaller plant would cover a significantly higher proportion of the plant

Table 3.4 Mean comparisons of kochia areas under desiccation progress curve (AUDPC) at Saskatoon and Scott, SK from 2012 to 2014. Estimate statements represent pre-planned comparisons of glyphosate with glyphosate tank-mixed with contact herbicides, glyphosate with contact herbicides alone, and glyphosate rates.

		Kochia- AUDPC††				
Herbicide	Rate	Saskatoon 2012	Saskatoon 2013	Saskatoon 2014	Scott 2013	Scott 2014
	(g ai/ae ha^{-1})					
Untreated	0	220 H	599 C	610 G	1563	1077 D
Glyphosate	450	494 G	696 BC	712 E-G	1511	1111 CD
Glyphosate	900	635 D-F	718 BC	907 D-F	1617	1164 BC
Pyraflufen-ethyl‡	20	508 FG	705 BC	669 FG	1598	975 D
Pyraflufen-ethyl + Glyphosate‡	20 + 450	666 DE	735 B	983 DE	1598	1130 CD
Pyraflufen-ethyl + Glyphosate‡	20 + 900	652 DE	712 BC	1050 CD	1581	1109 CD
Glufosinate	600	1149 A	1236 A	1375 AB	1623	1494 A
Glufosinate + Glyphosate	600 + 450	1154 A	1266 A	1336 AB	1596	1465 AB
Glufosinate + Glyphosate	600 + 900	1124 A	1324 A	1314 A-C	1576	1431 A-C
Flumioxazin¶	210	474 G	680 BC	893 D-F	1631	982 D
Flumioxazin + Glyphosate¶	210 + 450	482 G	669 BC	962 DE	1531	991 D
Flumioxazin + Glyphosate¶	210 + 900	708 D	680 BC	978 DE	1661	1022 D
Saflufenacil§	50	540 E-G	678 BC	847 D-G	1642	1049 D
Saflufenacil + Glyphosate†	36 + 450	542 E-G	713 BC	995 D	1594	1091 D
Saflufenacil + Glyphosate†	36 + 900	738 CD	696 BC	1060 B-D	1735	1136 CD
Diquat¶¶	415	921 B	1227 A	1501 A	1615	1590 A
Diquat +Glyphosate¶¶	415 + 450	867 BC	1268 A	1510 A	1636	1642 A
Diquat +Glyphosate¶¶	415 + 900	949 B	1278 A	1428 A	1627	1658 A
Estimate						
Glyphosate (low) vs. TMa (low)		-248***	-234***	-445***	-80	-153
Glyphosate (high) vs. TMa (high)		-200***	-259***	-220***	-19	-108
Glyphosate (low) vs. Contact		-224***	-208***	-345***	-110	-107
Glyphosate (high) vs. Contact		-84***	-187***	-150***	-5	-54
TMa (low) vs. TMa (high)		-92***	-8	-9	-45	-7

*, **, ***, significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

†† Means within a column followed by the same letter are not significantly different on the basis of $HSD_{0.05}$.

TMa denotes tank mix partners.

‡ Merge® at 1% v/v was added in pyraflufen-ethyl and the tank mixture of pyraflufen+glyphosate treatment.

¶ Agral 90® at 0.25% v/v was added in flumioxazin treatment and the tank mixture of flumioxazin+glyphosate treatment.

§ Merge® at 1 L ha^{-1} was added in saflufenacil treatment.

¶¶ Agral 90® at 0.1% v/v was added in diquat and the tank mixture of diquat+glyphosate treatment

Table 3.5 Mean comparisons of *B. juncea* areas under desiccation progress curve (AUDPC) at Saskatoon and Scott, SK from 2012 to 2014. Estimate statements represent pre-planned comparisons of glyphosate with glyphosate tank-mixed with contact herbicides, glyphosate with contact herbicides alone, and glyphosate rates.

		Juncea - AUDPC††				
Herbicide	Rate	Saskatoon 2012	Saskatoon 2013	Saskatoon 2014	Scott 2013	Scott 2014
	(g a.i./a.e. ha^{-1})					
Untreated	0	860 H	727 C	793 H	1442	1092 CD
Glyphosate	450	928 F-H	820 BC	906 F-G	1505	1079 CD
Glyphosate	900	1109 B-D	884 B	1036 E-G	1529	1085 CD
Pyraflufen-ethyl‡	20	895 GH	773 BC	880 GH	1518	971 D
Pyraflufen-ethyl + Glyphosate‡	20 + 450	1035 D-F	875 BC	1120 EF	1529	1123 CD
Pyraflufen-ethyl + Glyphosate‡	20 + 900	1091 C-E	888 B	1206 DE	1590	1056 CD
Glufosinate	600	1195 A-C	1358 A	1421 CD	1519	1506 A
Glufosinate + Glyphosate	600 + 450	1240 A	1362 A	1456 BC	1505	1490 AB
Glufosinate + Glyphosate	600 + 900	1205 AB	1409 A	1463 BC	1523	1372 A-C
Flumioxazin¶	210	895 GH	834 BC	1039 E-G	1609	925 D
Flumioxazin + Glyphosate¶	210 + 450	1031 D-F	837 BC	1128 E	1562	944 D
Flumioxazin + Glyphosate¶	210 + 900	1060 DE	807 BC	1128 E	1620	1072 CD
Saflufenacil§	50	891 GH	834 BC	1137 E	1587	1038 CD
Saflufenacil + Glyphosate†	36 + 450	981E-G	838 BC	1162 E	1496	1112 CD
Saflufenacil + Glyphosate†	36 + 900	1115 B-D	871 BC	1199 E	1637	1132 B-D
Diquat¶¶	415	1191 A-C	1434 A	1728 A	1511	1615 A
Diquat +Glyphosate¶¶	415 + 450	1193 A-C	1493 A	1692 A	1595	1644 A
Diquat +Glyphosate¶¶	415 + 900	1191 A-C	1481 A	1662 AB	1489	1684 A
Estimates						
Glyphosate (low) vs. TMa (low)		168***	-261***	-406***	-33	-184*
Glyphosate (high) vs. TMa (high)		-23	-208***	-296***	-43	-178*
Glyphosate (low) vs. Contact		-86***	-227***	-335***	-44	-132
Glyphosate (high) vs. Contact		95***	-163***	-205***	-19	-125
TMa (low) vs. TMa (high)		-36*	-10	-20	-34	-1

*, **, ***, significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

†† Means within a column followed by the same letter are not significantly different on the basis of $HSD_{0.05.}$

TMa denotes tank mix partners.

‡ Merge® at 1% v/v was added in pyraflufen-ethyl and the tank mixture of pyraflufen+glyphosate treatment.

¶ Agral 90® at 0.25% v/v was added in flumioxazin treatment and the tank mixture of flumioxazin+glyphosate treatment.

§ Merge® at 1 L ha^{-1} was added in saflufenacil treatment.

¶¶ Agral 90® at 0.1% v/v was added in diquat and the tank mixture of diquat+glyphosate treatment

compared to a larger plant and thus a greater proportion of the smaller plant will be affected compared to a larger plant.

Our results show that these herbicides benefited from the addition of glyphosate more than diquat or glufosinate did. However, they rarely attained similar AUDPC values as diquat or glufosinate which suggests that they are not as effective at drying down plant material and when mixed with glyphosate the glyphosate is providing much greater proportion of the dry-down compared to these herbicides alone.

3.4.2 Lentil Seed Yield and Weed Seed Production

Lentil seed yield was not significantly affected by treatments in any site-year (Table 3.6). Contrasts indicated that there was no significant decrease in lentil seed yield with the addition of glyphosate to the contact herbicides or between the contact herbicides and glyphosate (Table 3.7). Lentil seed yield was also not affected by the rate of glyphosate when applied alone or in combination with the contact herbicides. Lentil yield in these trials was considerably lower than provincial averages, likely due to the intense competition provided by the mature kochia and *juncea* in the plots.

Table 3.6 P-values derived from analysis of variance showing fixed factors combinations at Saskatoon and Scott, Saskatchewan in 2012-2014.

Site-year	Lentil Yield	Kochia Yield	*Juncea* Yield	Kochia TSW	*Juncea* TSW	Straw Moisture	Seed Moisture
Saskatoon 2012	0.4106	<.0001***	0.4149	<.0001***	0.6815	<.0001***	<.0001***
Saskatoon 2013	0.9632	0.4077	0.0260*	0.1472	0.4459	0.0015**	0.0004**
Saskatoon 2014	0.3794	0.3320	0.0282*	0.6455	0.0133*	<.0001***	<.0005**
Scott 2013	0.3801	0.0220*	0.4794	<.0001***	0.0724	<.0001***	<.0001***
Scott 2014	0.8600	0.1176	0.0015**	0.1660	0.2920	<.0001***	<.0001***

*, **, ***, significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

Herbicide treatments were found to significantly influence seed production of kochia (Table 3.8). Glufosinate + glyphosate (450 g a.e. ha^{-1}) reduced the kochia seed production to 11,899 seeds m^{-2}, which was statistically lower than pyraflufen-ethyl (19,480 seeds m^{-2}) and saflufenacil (19,020 seeds m^{-2}) when both were tank mixed with glyphosate (450 g a.e. ha^{-1}). However, these values were not statistically different from the untreated check (18,218 seeds m^{-2}). Contrasts indicated that tank mixes with a high rate of glyphosate were more effective at reducing kochia seed production compared to tank mixes with a low rate of glyphosate (Table 3.8). *Juncea* seed production was not impacted by any treatment, although contrasts revealed that contact herbicides were more effective at reducing *juncea* seed production compared to glyphosate applied alone at the low rate (Table 3.8).

Thousand-seed weight (TSW) of *juncea* was only significantly affected by the treatments at Saskatoon in 2014, and kochia TSW was only affected at Saskatoon in 2012 and Scott in 2013 (Table 3.6). At the 2012 Saskatoon location, glufosinate applied alone or with glyphosate reduced kochia TSW by 37 to 49% compared to the untreated check (Table 3.9). Although the tank mix of glufosinate and diquat were significantly different from the untreated check for kochia TSW, these treatments did not differ from glufosinate applied alone. Apart from glufosinate, both glyphosate tank-mix combinations with diquat significantly reduced kochia TSW 28% more than the untreated check.

Although statistically significant, the impact of treatments on the TSW of kochia and *juncea* was not substantial at either location in 2013 and 2014 (Tables 3.9 and 3.10). At Scott in 2013, only the TSW of kochia was significantly affected by herbicide treatments. Specifically, glufosinate + glyphosate (900 g a.e. ha^{-1}) was the only treatment that significantly reduced kochia TSW (40%). *Juncea* TSW was only significantly affected by treatments at Saskatoon in 2014. The high rate of glyphosate reduced *juncea* TSW by 33% (Table 3.10). No other treatment significantly affected TSW for *juncea* or kochia in this site-year.

Both weed seed production and TSW appeared to be influenced by environmental conditions. Abiotic factors that can affect herbicide efficacy and weed growth include but are not limited to the availability of water, nutrients, and temperature. These factors can affect weed maturity, weed stand, and weed physiology as weeds can adapt to different environments in order to produce successful offspring (Varanasi et al. 2016). Conditions that allow weeds to mature quicker could allow for more mature plants and seeds in a pre-harvest herbicide application. This in turn may reduce the effectiveness of applying herbicides to reduce weed seed production and future seedling viability and vigour.

Table 3.7 Mean comparisons of lentil seed yield at Saskatoon and Scott, SK from 2012 to 2014. Estimate statements represent pre-planned comparisons of glyphosate with glyphosate tank-mixed with contact herbicides, glyphosate with contact herbicides alone, and glyphosate rates.

Treatment	Rate	Yield
	(g a.i./a.e. ha^{-1})	(kg/ha^{-1})
Untreated	0	547
Glyphosate	450	525
Glyphosate	900	520
Pyraflufen-ethyl	20	578
Pyraflufen-ethyl + Glyphosate	20 + 450	508
Pyraflufen-ethyl + Glyphosate	20 + 900	557
Glufosinate	600	511
Glufosinate + Glyphosate	600 + 450	503
Glufosinate + Glyphosate	600 + 900	505
Flumioxazin	210	565
Flumioxazin + Glyphosate	210 + 450	526
Flumioxazin + Glyphosate	210 + 900	501
Saflufenacil	50	537
Saflufenacil + Glyphosate	36 + 450	554
Saflufenacil +Glyphosate	36 + 900	481
Diquat	415	561
Diquat +Glyphosate	415 + 450	516
Diquat +Glyphosate	415 + 900	510
Estimates		
Glyphosate (low) vs. TMa (low)		3
Glyphosate (high) vs. TMa (high)		10
Glyphosate (low) vs. Contact		-26
Glyphosate (high) vs. Contact		-30
TM (low) vs. TM (high)		10

‡ Merge® at 1% v/v was added in pyraflufen-ethyl and the tank mixture of pyraflufen-ethyl+glyphosate treatment.

TMa denotes tank mix partners.

¶ Agral 90® at 0.25% v/v was added in flumioxazin treatment and the tank mixture of flumioxazin+glyphosate treatment.

§ Merge® at 1 L ha^{-1} was added in saflufenacil treatment.

† Merge® at 0.5 L ha^{-1} was added in the tank mixture of saflufenacil+glyphosate treatment.

¶¶ Agral 90® at 0.1% v/v was added in diquat and the tank mixture of diquat+glyphosate treatment

Table 3.8 Kochia and *B. juncea* seed production with various herbicide combinations applied pre-harvest at Saskatoon and Scott, Saskatchewan in 2012-2014.

Herbicide	Rate	Seed Production Kochia	*Juncea*
	(g a.i./a.e. ha^{-1})	(seeds per m^{-2})	
Untreated	0	18218 AB	34976
Glyphosate	450	18365 AB	38487
Glyphosate	900	14545 AB	36420
Pyraflufen-ethyl‡	20	18038 AB	32468
Pyraflufen-ethyl + Glyphosate‡	20 + 450	19480 A	34518
Pyraflufen-ethyl + Glyphosate‡	20 + 900	15276 AB	32404
Glufosinate	600	13250AB	37613
Glufosinate + Glyphosate	600 + 450	11899 B	31350
Glufosinate + Glyphosate	600 + 900	12385 AB	30255
Flumioxazin¶	210	16889 AB	30783
Flumioxazin + Glyphosate¶	210 + 450	16140 AB	34808
Flumioxazin + Glyphosate¶	210 + 900	15014 AB	35785
Saflufenacil§	50	17848 AB	34273
Saflufenacil + Glyphosate†	36 + 450	19020 A	36355
Saflufenacil + Glyphosate†	36 + 900	16908 AB	31581
Diquat¶¶	415	15871 AB	30360
Diquat +Glyphosate¶¶	415 + 450	18281 AB	35123
Diquat +Glyphosate¶¶	415 + 900	14064 AB	31592
Estimates			
Glyphosate (low) vs. TMa (low)		1401	4056
Glyphosate (high) vs. TMa (high)		-185	4097
Glyphosate (low) vs. Contact		1986	5387 *
Glyphosate (high) vs. Contact		-1835	3321
TMa (low) vs. TMa (high)		2235 *	2108

*, **, ***, significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
†† Means within a column followed by the same letter are not significantly different on the basis of $HSD_{0.05}$.
TMa denotes tank mix partners.
‡ Merge® at 1% v/v was added in pyraflufen-ethyl and the tank mixture of pyraflufen+glyphosate treatment.
¶ Agral 90® at 0.25% v/v was added in flumioxazin treatment and the tank mixture of flumioxazin+glyphosate treatment.
§ Merge® at 1 L ha-1 was added in saflufenacil treatment.
¶¶ Agral 90® at 0.1% v/v was added in diquat and the tank mixture of diquat+glyphosate treatment

Table 3.9 Kochia thousand seed weight (TSW) with various herbicide combinations applied pre-harvest at Saskatoon and Scott, Saskatchewan in 2012-2014.

Herbicide	Rate	Kochia Thousand Seed Weight				
		Saskatoon 2012	Saskatoon 2013	Saskatoon 2014	Scott 2013	Scott 2014
	(g a.i./a.e. ha^{-1})			(g)		
Untreated	0	0.68 A	0.75	0.73	0.78 AB	0.71
Glyphosate	450	0.63 A-C	0.56	0.67	0.77 AB	0.69
Glyphosate	900	0.61 A-C	0.65	0.55	0.7 A-C	0.56
Pyraflufen-ethyl‡	20	0.58 A-D	0.73	0.71	0.79 AB	0.73
Pyraflufen-ethyl + Glyphosate‡	20 + 450	0.53 A-E	0.58	0.64	0.63 A-C	0.67
Pyraflufen-ethyl + Glyphosate‡	20 + 900	0.56 A-D	0.69	0.69	0.77 AB	0.75
Glufosinate	600	0.35 F	0.53	0.66	0.69 A-C	0.65
Glufosinate + Glyphosate	600 + 450	0.38 EF	0.63	0.56	0.62 BC	0.67
Glufosinate + Glyphosate	600 + 900	0.43 D-F	0.61	0.61	0.47 C	0.63
Flumioxazin¶	210	0.65 AB	0.7	0.73	0.75 AB	0.63
Flumioxazin + Glyphosate¶	210 + 450	0.57 A-D	0.67	0.57	0.71 A-C	0.65
Flumioxazin + Glyphosate¶	210 + 900	0.64 A-C	0.61	0.64	0.8 AB	0.7
Saflufenacil§	50	0.64 A-C	0.54	0.59	0.71 A-C	0.56
Saflufenacil + Glyphosate†	36 + 450	0.64 A-C	0.6	0.65	0.8 AB	0.67
Saflufenacil + Glyphosate†	36 + 900	0.57 A-D	0.74	0.66	0.87 A	0.77
Diquat¶¶	415	0.53 A-E	0.57	0.53	0.56 BC	0.68
Diquat +Glyphosate¶¶	415 + 450	0.49 C-F	0.62	0.69	0.67 A-C	0.65
Diquat +Glyphosate¶¶	415 + 900	0.49 B-F	0.67	0.67	0.73 AB	0.68
Estimates						
Glyphosate (low) vs. TMa (low)		0.1 **	-0.1	0	0.09	0.03
Glyphosate (high) vs. TMa (high)		0.1	0	-0.1	-0.02	-0.14 **
Glyphosate (low) vs. Contact		0.07 *	-0.1	0	0.07	-0.04
Glyphosate (high) vs. Contact		0.1	0	-0.1	0	-0.08
TMa (low) vs. TMa (high)		-0.01	0	0	-0.04	-0.04

*, **,*** , significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

†† Means within a column followed by the same letter are not significantly different on the basis of $HSD_{0.05}$.

TMa denotes tank mix partners.

‡ Merge® at 1% v/v was added in pyraflufen-ethyl and the tank mixture of pyraflufen+glyphosate treatment.

¶ Agral 90® at 0.25% v/v was added in flumioxazin treatment and the tank mixture of flumioxazin+glyphosate treatment.

§ Merge® at 1 L ha-1 was added in saflufenacil treatment.

¶¶ Agral 90® at 0.1% v/v was added in diquat and the tank mixture of diquat+glyphosate treatment

Table 3.10 *B. juncea* thousand seed weight (TSW) with various herbicide combinations applied pre-harvest at Saskatoon and Scott, Saskatchewan in 2012-2014.

Herbicide	Rate	*Juncea* Thousand Seed Weight				
		Saskatoon 2012	Saskatoon 2013	Saskatoon 2014	Scott 2013	Scott 2014
	(g a.i./a.e. ha^{-1})			(g)		
Untreated	0	2.63	2.82	3.56 A	3.03	2.89
Glyphosate	450	2.54	2.31	2.90 AB	3.04	2.69
Glyphosate	900	2.86	2.8	2.37 B	3.0	2.84
Pyraflufen-ethyl‡	20	2.54	2.65	3.32 AB	3.44	2.7
Pyraflufen-ethyl + Glyphosate‡	20 + 450	2.66	2.31	3.52 AB	2.83	2.76
Pyraflufen-ethyl + Glyphosate‡	20 + 900	2.74	2.75	3.34 AB	2.99	2.8
Glufosinate	600	2.63	2.3	2.54 AB	3.16	2.53
Glufosinate + Glyphosate	600 + 450	2.79	2.44	2.95 AB	2.81	2.6
Glufosinate + Glyphosate	600 + 900	2.69	2.54	2.94 AB	2.87	2.71
Flumioxazin¶	210	2.84	2.66	3.44 AB	2.95	2.96
Flumioxazin + Glyphosate¶	210 + 450	2.62	2.67	3.10 AB	2.89	2.85
Flumioxazin + Glyphosate¶	210 + 900	2.81	2.68	3.34 AB	2.95	2.78
Saflufenacil§	50	2.44	2.48	2.86 AB	2.95	2.84
Saflufenacil + Glyphosate†	36 + 450	2.57	2.26	3.35 AB	3.01	2.7
Saflufenacil + Glyphosate†	36 + 900	2.47	2.34	2.95 AB	2.83	2.67
Diquat¶¶	415	2.65	2.31	3.30 AB	2.89	2.61
Diquat +Glyphosate¶¶	415 + 450	2.73	2.39	2.73 AB	3.05	2.62
Diquat +Glyphosate¶¶	415 + 900	2.75	2.64	3.01 AB	3.28	2.62
Estimates						
Glyphosate (low) vs. TMa (low)		-0.13	-0.1	-0.23	0.12	-0.01
Glyphosate (high) vs. TMa (high)		0.16	0.21	-0.74 **	0.01	0.12
Glyphosate (low) vs. Contact		-0.07	-0.16	-0.19	-0.03	-0.03
Glyphosate (high) vs. Contact		0.24	0.32	-0.72 **	-0.07	0.11
TMa (low) vs. TMa (high)		-0.01	-0.17	0.02	-0.06	0

*, **,***, significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

†† Means within a column followed by the same letter are not significantly different on the basis of $HSD_{0.05}$.

TMa denotes tank mix partners.

‡ Merge® at 1% v/v was added in pyraflufen-ethyl and the tank mixture of pyraflufen+glyphosate treatment.

¶ Agral 90® at 0.25% v/v was added in flumioxazin treatment and the tank mixture of flumioxazin+glyphosate treatment.

§ Merge® at 1 L ha-1 was added in saflufenacil treatment.

¶¶ Agral 90® at 0.1% v/v was added in diquat and the tank mixture of diquat+glyphosate treatment

Environmental factors that can affect herbicide efficacy include: light, carbon dioxide, temperature, relative humidity, precipitation, soil moisture and wind (Combellack 1982; Devine et al. 1993; Devine 1989, Levene and Owen 1995; Price 1983). These factors can influence how a herbicide deposits on a plant leaf, penetrates the cuticle and translocates to the target site. Overall, the addition of glyphosate to the contact herbicides did not appear to have an effect on TSW of either weed species compared to glyphosate alone. Zhang et al. (2016) provided evidence that neither saflufenacil nor glyphosate applied alone or in combination had a significant effect on the TSW of lentil when applied at 30% seed moisture. This suggests that the closer a seed is to full physiological maturity, the less impact a herbicide has on the final seed size; desiccant applications applied prior to 30% seed moisture negatively affected lentil seed weight in that study.

The results of this study showed that there was no significant herbicide effect on lentil yield or the TSW when contact herbicides were applied alone or in combination with glyphosate at 30% dry-down (Table 3.7). Zhang et al. (2016) observed similar results in lentil with these same treatments. Other studies have also found that applying these herbicides at the correct timing does not affect the final yield or the TSW of other pulse crops including dry bean and soybean (Bennett and Shaw 2000a; McNaughton et al. 2015). Bennet and Shaw (2000a) and McNaughton et al. (2015) observed decreases in crop seed weight when pre-harvest herbicides were applied too early in pulse crops. Similarly, Zhang et al. (2017) found that early application timings can reduce lentil TSW if saflufenacil is applied prior to 50% seed moisture. This crop stage and herbicide timing relationship suggests that application timings have a greater impact on seed weight and total seed production of treated plants compared to herbicide applications when the seed is more mature and drier at 30%. In the current study, lentil yield was not affected by the herbicide treatments, while there was some effect of the herbicide treatments on kochia and *juncea* TSW in a few of the site-years. The treatments were timed for 30% lentil seed moisture, meaning that the majority of the lentil seed was fully developed and not sensitive to the herbicide treatments. While the kochia and *juncea* TSW was not consistently reduced throughout every site-year, the variability could suggest that the weed seeds were less mature at the time of application in instances where the TSW for each species was significantly reduced.

Treatment effects on weed seed production and TSW for both kochia and *juncea* were inconsistent. Lentil seed moisture timing was used to decide when to apply the treatments, probably leading to slight differences in weed maturity at application across site-years. This means that kochia and *juncea* maturity at the time of application may not have been consistent across site-years, potentially leading to inconsistent treatment efficacy throughout this study. In this trial, kochia was often in late bloom or had just finished blooming, while the *juncea* had often finished flowering weeks before the pre-harvest application. Studies researching late-season weed management found that flowering is the most effective time for reducing viable seed production in a broad spectrum of weeds including pitted morning glory (Walker and Oliver 2008). Kumar and Jha (2015) reported that at the early bloom stage, several herbicide combinations, including glyphosate and glufosinate, completely eliminated weed seed shed in kochia in post-harvest wheat stubble. A Montana study indicated that reductions in kochia seed production were not significant when herbicides were applied after the first week in September as sustainable amounts of seed had finished developing (Mickelson et al. 2004). Weeds that are more mature may be less susceptible to weed seed reductions from herbicides as they have already developed most of their offspring, with the mature offspring needing fewer resources to finish developing (Isaac et al. 1989; Jeffery et al. 1981). This could be demonstrated in this study where *juncea* seeds that were more mature at the time of application and thus less affected by the herbicide treatments in comparison to the kochia. In fact, only a 900 g a.e. ha^{-1} of glyphosate significantly lowered the TSW and in only one single site-year. Conversely, kochia was significantly affected in multiple site-years with greater significant treatment differences such as glufosinate treatments in 2012 at Saskatoon and 2013 at Scott.

Application timing is an important factor in determining the success of a late-season herbicide application in reducing weed seed production and TSW (Isaacs et al. 1989; Ratnayake and Shaw 1992; Clay and Griffin 2000). Clay and Griffin (2000) examined the effects of several late season herbicides on the seed production of *Xanthium strumarium* L., *Sesbania exaltata* (Raf.) Cory, and *Senna obtusifolia* L. at three different application timings: initial seed set, mid-seed fill and physiological maturity. They found that in most site-years glyphosate significantly influenced seed production and seed weight in all three weeds when applied at the onset of seed initiation of each species (Clay and Griffin 2000). Other studies also indicate that delaying the application of a harvest aid from initial seed set to mid-seed fill results in greater seed production, depending on the weed species (Isaacs et al. 1989; Ratnayake and Shaw 1992). While these studies indicate that an early application timing is important for reducing seed production, they also indicate that later applications can impact these populations by reducing the fitness of weed seeds, which could in turn reduce the number of seeds entering the soil seedbank. While this benefit is not immediately realized, weed seeds with poor viability and vigour may ultimately reduce the number of weed seedlings that establish in future growing seasons. Alternatively, the reproductive fitness of weeds could be reduced, altering the number of seeds produced in a growing season. Reducing weed seed contributions to the seed bank is important in reducing the negative impact that weeds have on crop production (Bagavathiannan and Norsworthy 2012). Moreover, less competitive weed seeds caused by late-season herbicide applications may be more susceptible to alternative weed management tactics, which in turn will further decrease weed seed contributions to the seed bank.

Results from this study suggest that herbicide treatments become less effective at reducing weed seed production and TSW as the weeds progress through the reproductive stages. Once weeds reach a maturity where the majority of seeds have developed, herbicide treatments cannot substantially reduce seed production as the seed has already developed. To maximize the reduction in weed seed additions to the seed bank, with the use of pre-harvest herbicides, growers need to delay the development to kochia and wild mustard as much as possible. Using pre-emergent herbicides or other mechanisms to delay the growth and development of problem weeds like kochia and wild mustard will help to ensure that the weeds are still immature at the time of application. By delaying the development of these weeds in comparison to the crop lentil producers may find that they have greater efficacy and reduced seed bank additions, particularly if the weeds are in or closer to their bloom stage than they were in this study.

3.4.3 Harvest Straw Moisture

There was a significant interaction between site-year and herbicide and thus it was decided to analyze straw moisture data within site-year (Table 3.11). At Saskatoon in 2012, all treatments with the exception of pyraflufen and diquat applied alone significantly reduced harvest straw moisture of lentil and weeds relative to the untreated check (Table 3.12). Overall, increasing the rate of glyphosate further decreased straw moisture, with glyphosate (900 g ae ha^{-1} rate) applied alone having the greatest impact, reducing straw moisture by 50%. Pyraflufen, glufosinate, flumioxazin, saflufenacil and diquat, all tank-mixed with glyphosate (900 g ae ha^{-1} rate) reduced straw moisture by 30%, 34%, 40%, 35%, and 13% compared to the untreated check, respectively. This trend was also observed in Saskatoon in 2013 and 2014 as well, but with insignificant differences between the treatments (P>0.05).

At Scott in 2013, the addition of glyphosate as a tank mix herbicide only significantly reduced straw moisture compared to the contact herbicides applied alone when it was added to pyraflufen (both rates) and flumioxazin at the half rate. (Table 3.11). At Scott in 2014, glyphosate applied alone at both rates was not as effective at reducing straw moisture as it was in a tank-mix. Tank-mixes with a full rate of glyphosate reduced straw moisture in comparison to the untreated check, with a diquat tank-mix providing the greatest reduction of straw moisture at 60%. Overall contrasts showed that glyphosate at 450 g a.e. ha^{-1} was also more effective as a tank mix compared to when it was applied alone, though no individual treatment provided greater reductions in straw moisture.

Overall the addition of glyphosate to a tank mix with pyraflufen, flumioxazin, and saflufenacil was more effective at reducing straw moisture than combining glyphosate with diquat or glufosinate (Table 3.11). Typically, glyphosate applied alone provided the greatest decrease in straw moisture with the exception of Scott in 2014, where the tank-mixes provided greater straw moisture reductions. Single degree of freedom contrasts for straw moisture showed that the contact herbicides applied alone were generally less effective at reducing straw moisture than the full rate of glyphosate applied alone. Furthermore, increasing glyphosate from a half to full rate generally further decreased straw moisture. The exception was Scott in 2014, where diquat (56%) and glufosinate (50%) provided greater dry-down alone compared to the half (34%) or full (16%) rates of glyphosate. Overall, glyphosate alone further decreased moisture by 11-16% compared to the full rate tank-mixes. While different treatments provided varying levels of efficacy, a full rate of glyphosate, diquat, and glufosinate provided the most consistent level of dry-down across all site-years.

Similar to straw moisture, there were significant treatment differences in seed moisture across all site-years (Table 3.12). Except for Scott in 2014, glyphosate at the 900 g ae ha^{-1} significantly reduced seed moisture by 40 to 50% across all site-years. Pyraflufen applied alone significantly reduced seed moisture in 2013 at both the Saskatoon and Scott locations, by 22% and 35% respectively. Similar to glyphosate, glufosinate significantly reduced seed moisture by 44 to 67% in all site-years except for Scott in 2014. When applied alone pyraflufen had no significant effect on seed moisture in any site-years and saflufenacil only significantly reduced moisture at Scott in 2013 by 47%. Compared to the untreated check, diquat applied alone significantly reduced seed moisture in Saskatoon in 2012 and 2013 and Scott 2013 by 24%, 24%, and 48% respectively. Contrasts showed that tank-mixing glyphosate was only moderately effective at further reducing seed moisture compared to glyphosate alone. The addition of glyphosate to glufosinate or diquat did not significantly impact seed moisture compared to the two herbicides applied alone. Saflufenacil, flumioxazin and pyraflufen were only slightly more impacted by the addition of glyphosate, but the impact was variable across site-years and glyphosate rates.

Reducing plant moisture through desiccation had a positive effect on harvestability of a crop. Desiccating allows for early harvest by drying down green plants and increasing the speed a combine can harvest a crop. Ellis et al. (1998) reported that glufosinate, glyphosate, and several other herbicides increased the harvestability of soybean significantly over the untreated check. Further, combine speeds in the glyphosate and glufosinate treatments were similar to the weed free check (Ellis et al., 1998). In this current study, the consistent ability of glyphosate, glufosinate, and diquat to reduce straw moisture is consistent with results from Zhang et al. (2016) and Soltani et al. (2013). While applications of diquat and glufosinate alone consistently reduced straw moisture more than the untreated check, applications of saflufenacil, flumioxazin, and pyraflufen did not. Our results indicate that glyphosate, glufosinate and diquat would have the greatest potential to increase the harvestability and decrease the straw moisture of lentil fields infested with either kochia or wild mustard.

Table 3.11 Harvest straw moisture at Saskatoon and Scott, SK from 2012 to 2014. Estimate statements represent differences between herbicide treatments in harvest straw moisture.

Herbicide	Rate	Straw moisture				
		Saskatoon 2012	Saskatoon 2013	Saskatoon 2014	Scott 2013	Scott 2014
	(g a.i./a.e. ha^{-1})			(%)		
Untreated	0	46.2 A	39.4 AB	62.0 A	40.6 A	47.3 A
Glyphosate	450	37.2 C-E	33.9 B-E	46.3 A-D	19.4 CD	31.1 A-D
Glyphosate	900	23.1 J	28.0 E	36.0 CD	12.4 E-G	39.5 AB
Pyraflufen-ethyl‡	20	43.9AB	39.9 AB	59.7 AB	35.6 AB	46.2 AB
Pyraflufen-ethyl + Glyphosate‡	20 + 450	38.1 C-E	34.7 B-D	48.4 A-C	18.2 C-E	33.5 A-D
Pyraflufen-ethyl + Glyphosate‡	20 + 900	32.3F-H	33.6 B-E	28.3 CD	14.8 D-G	28.9 A-D
Glufosinate	600	32.3 F-H	36.3 A-C	45.8 A-D	18.3 C-E	23.7 CD
Glufosinate + Glyphosate	600 + 450	29.8 HI	36.2 A-C	39.2 CD	17.3 C-E	20.9 CD
Glufosinate + Glyphosate	600 + 900	30.7 G-I	30.4 C-E	41.5 B-D	16.1 C-G	22.4 CD
Flumioxazin¶	210	40.6 BC	40.0 AB	58.9 AB	36.0 AB	45.9 AB
Flumioxazin + Glyphosate¶	210 + 450	35.2 E-G	36.4 A-C	48.2 A-C	20.3 CD	36.8 A-D
Flumioxazin + Glyphosate¶	210 + 900	27.3 IJ	30.4 C-E	38.7 CD	34.0 B	27.5 A-D
Saflufenacil§	50	41.4 BC	41.7 A	62.0 A	10.8 G	47.0 AB
Saflufenacil + Glyphosate†	36 + 450	35.6 D-F	34.1 B-E	44.9 A-D	21.6 C	31.1 A-D
Saflufenacil + Glyphosate†	36 + 900	30.1 HI	28.5 DE	33.7 CD	11.0 FG	27.3 B-D
Diquat¶¶	415	41.8 A-C	37.8 AB	37.3 CD	16.6 C-G	21.0 CD
Diquat +Glyphosate¶¶	415 + 450	39.5 B-E	34.3 B-E	45.2 A-D	17.0 C-F	24.3 CD
Diquat +Glyphosate¶¶	415 + 900	40.4 B-D	34.6 B-E	42.4 A-D	16.1C-G	18.9 D
Estimates						
Glyphosate (low) vs. TMa (low)		1.5	-1.2	1.1	0.3	-3.4
Glyphosate (high) vs. TMa (high)		-9.0***	-3.4	-0.9	-6.0*	10.3**
Glyphosate (low) vs. Contact		-2.8	-5.2*	-6.4	0.7	-10.8**
Glyphosate (high) vs. Contact		-16.9***	-11.1***	-16.7***	-11.0***	-1.4**
TMa (low) vs. TMa (high)		3.5**	3.6*	8.3**	-0.06	4.3

*, **, ***, significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

†† Means within a column followed by the same letter are not significantly different on the basis of $HSD_{0.05}$.

TMa denotes tank mix partners.

‡ Merge® at 1% v/v was added in pyraflufen-ethyl and the tank mixture of pyraflufen+glyphosate treatment.

¶ Agral 90® at 0.25% v/v was added in flumioxazin treatment and the tank mixture of flumioxazin+glyphosate treatment.

§ Merge® at 1 L ha-1 was added in saflufenacil treatment.

¶¶ Agral 90® at 0.1% v/v was added in diquat and the tank mixture of diquat+glyphosate treatment

Table 3.12 Combined seed moisture at Saskatoon and Scott, SK from 2012 to 2014. Estimate statements represent differences between herbicide treatments in harvest straw moisture.

Herbicide	Rate	Seed moisture				
		Saskatoon 2012	Saskatoon 2013	Saskatoon 2014	Scott 2013	Scott 2014
	(g a.i./a.e. ha^{-1})			(%)		
Untreated	0	34.38 A	17.05 A	28.9 A	5.08 A	16.4 A-C
Glyphosate	450	23.09 C-F	12.69 B-E	19.9 A-C	3.43 BC	15.3 BC
Glyphosate	900	19.66 EF	10.29 D-F	14.7 BC	2.73 C-F	14.4 BC
Pyraflufen-ethyl‡	20	30.96 AB	13.36 B-D	23.8 AB	3.28 B-E	16.6 A-C
Pyraflufen-ethyl + Glyphosate‡	20 + 450	26.54 B-E	11.83 C-E	17.7 A-C	2.80 C-F	15.1 BC
Pyraflufen-ethyl + Glyphosate‡	20 + 900	20.69 D-F	11.64 C-E	13.3 BC	2.55 C-F	13.5 BC
Glufosinate	600	11.34 G	9.84 D-F	12.6 BC	2.25 F	11.8 BC
Glufosinate + Glyphosate	600 + 450	11.97 G	9.22 EF	9.6 C	2.45 D-F	10.0 C
Glufosinate + Glyphosate	600 + 900	11.84 G	7.89 F	13.4 BC	2.58 C-F	10.3 BC
Flumioxazin¶	210	28.09 A-C	15.68 AB	25.5 AB	4.13 AB	22.2 A
Flumioxazin + Glyphosate¶	210 + 450	27.34 B-D	12.15 B-E	17.2 A-C	2.83 C-F	16.9 AB
Flumioxazin + Glyphosate¶	210 + 900	17.70 FG	11.16 D-F	17.3 A-C	3.40 B-D	16.1 A-C
Saflufenacil§	50	28.14 A-C	15.09 A-C	23.3 A-C	2.68 C-F	14.9 BC
Saflufenacil + Glyphosate†	36 + 450	24.29 B-F	12.62 B-E	16.5 A-C	2.68 C-F	13.4 BC
Saflufenacil + Glyphosate†	36 + 900	23.43 C-F	9.97 D-F	16.2 A-C	2.35 EF	12.3 BC
Diquat¶¶	415	26.29 B-E	12.90 B-D	18.9 A-C	2.65 C-F	10.5 BC
Diquat +Glyphosate¶¶	415 + 450	24.62 B-E	10.23 D-F	16.0 A-C	2.93 C-F	11.0 BC
Diquat +Glyphosate¶¶	415 + 900	21.74 C-F	13.23 B-D	16.3 A-C	2.68 C-F	10.7 BC
Estimates						
Glyphosate (low) vs. TMa (low)		0.1	1.4	4.5*	0.7*	-0.5
Glyphosate (high) vs. TMa (high)		0.6	-0.5	-0.6	0	1.8
Glyphosate (low) vs. Contact		-1.9	-0.1	1.1	0.4	-1.8
Glyphosate (high) vs. Contact		-5.3	-2.5*	-4.1*	-0.3	-0.2
TMa (low) vs. TMa (high)		3.9*	0.4	0.1	0	0.7

*, **, *** , significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

†† Means within a column followed by the same letter are not significantly different on the basis of $HSD_{0.05}$.

TMa denotes tank mix partners.

‡ Merge® at 1% v/v was added in pyraflufen-ethyl and the tank mixture of pyraflufen+glyphosate treatment.

¶ Agral 90® at 0.25% v/v was added in flumioxazin treatment and the tank mixture of flumioxazin+glyphosate treatment.

§ Merge® at 1 L ha-1 was added in saflufenacil treatment.

¶¶ Agral 90® at 0.1% v/v was added in diquat and the tank mixture of diquat+glyphosate treatment

3.5 Conclusion

Glufosinate (600 g a.i. ha^{-1}) and diquat (415 g a.i. g ha^{-1}) applied alone or in combination with glyphosate provided greater dry down and desiccation of kochia and *juncea* plants compared to saflufenacil, flumioxazin, and pyraflufen applied alone or in a glyphosate tank mix. Overall, tank-mixing glyphosate with glufosinate and diquat increased the desiccation efficacy compared to glyphosate alone but did not consistently reduce weed seed production and had limited influence on lentil TSW. This research suggests that like crops, desiccation timing can impact weed seed production. The results indicate applications of diquat or glufosinate alone, or tank-mixed with glyphosate, will have the most significant impact on increasing lentil harvestability and provide the greatest reduction of weed seed production.

While diquat and glufosinate provided the most consistent dry-down and weed reduction in this study there are limits to how growers can currently use these products for pre-harvest. Current maximum residue levels (MRLs) are set for main export markets for diquat and glyphosate, but there are no current MRLs for glufosinate in lentil. Further research into glufosinate seed residue will be important in order to provide growers with the best pre-harvest herbicide option in lentil to dry-down and reduce seed production of kochia and wild mustard. Diquat does not have any registered tank mixes, meaning it can only be applied alone. For lentil producers looking to dry-down problem kochia and wild mustard in lentil and proactively manage glyphosate resistance, a tank mix combination of saflufenacil and a glyphosate (900 g ae ha^{-1} rate) in red lentil is the best current option until further work is done on glufosinate and diquat.

4.0 Influence of pre-harvest herbicides on the viability and vigour of treated weed seeds

4.1 Introduction

Herbicides are an effective weed management tool, but their extensive use has led to the evolution of herbicide resistant weed species (Preston and Powles 2002). There are several different herbicide resistance mechanisms including target site resistance and metabolic resistance. For resistance to evolve, a plant must have a heritable mechanism or trait that allows it to survive a herbicide application, produce offspring that can reach physiological maturity and deposit new weeds with the same resistance genes into the seedbank (Cobb and Reade 2014). These weed species continue to grow, mature, and set seed and increase the number of resistant biotypes in a field. This continues unless a different herbicide mechanism of action is used, or another control option is selected. Herbicide resistant seeds can germinate in future years and compete with the subsequent crops (Walker and Oliver 2008). To help minimize the rate of evolution of herbicide resistant weeds, weed control through multiple mechanisms of action (such as crop rotation and mechanical means) need to be incorporated into herbicide programs utilizing herbicides with different mechanisms of action (Norsworthy et al. 2010).

In Canada, acceptable weed control as defined by the Pest Management Regulatory Agency includes a herbicide that provides weed control of at least 80% (PMRA 2016). This means that in many cases when a herbicide is being used, not all of the target weeds are being fully controlled. These weed escapes may be able to continue to mature and set seed, potentially furthering the spread of that particular weed species. The zero-tolerance threshold is being studied as a mechanism to reduce weed pressure and herbicide resistance (Bagavathiannan and Norsworthy 2012; Norsworthy et al. 2012). To stop the spread of resistant weeds, the zero-tolerance strategy suggests that no weed can be allowed to reach physiological maturity and deposit seed into the seed bank (Bagavathiannan and Norsworthy 2012). This approach is based around using every avenue of IPM to stop the development of seed production in mature weeds. From a chemical approach, utilizing pre-harvest herbicides is one of the application timings that can be used to control late emerging weeds or herbicide resistant weeds to achieve zero-tolerance. Pre-harvest herbicides are often used to improve harvest quality and efficiency as late season weeds typically have minimal impacts on crop yield. However, research has shown that a pre-harvest application can also reduce weed seed production and seedling vigour (Isaacs et al. 1989; Ratnayake and Shaw 1992; Bennett and Shaw 2000b).

In lentil (*Lens culinaris* Medik), weeds are a major challenge and can often cause significant yield losses (Swanton et al. 1993; Tepe et al. 2004). While yield loss due to weeds can be significant in any row crop, lentil tends to be more susceptible to this type of loss due to a short growth habit and poor early season vigour. Complete crop failure can occur in extreme cases from overwhelming weed pressure (Elkoca et al. 2004; Brand et al. 2007). For Saskatchewan lentil producers, the use of imidazolinone tolerant (i.e. Group 2 tolerant) lentil varieties has become increasingly popular as they control a much broader range of weeds compared to the herbicides used in a conventional lentil program. Group 2 herbicides are applied on approximately 30% of Canadian prairie cropped acres (Beckie et al., 2007). Due to the extensive use of these herbicides, there has been an increase in imidazolinone resistant weeds (Heap 2016). Wild mustard (*Sinapis arvensis* L.) and kochia (*Kochia scoparia* L.) are two of the most problematic weeds in imidazolinone tolerant lentil and both have populations with evolved ALS-inhibitor resistance (Wall 1993; Beckie et al. 2013, 2015; Heap 2017). When in-crop herbicide applications fail to control weeds, the next opportunity for herbicidal weed control is prior to harvest.

Lentil is an indeterminate crop and so producers often use desiccants to improve dry-down and harvest efficiency. Instead of using pre-harvest herbicides based on economic thresholds, utilizing these herbicides based on a zero-tolerance approach may be more appropriate in some cases, particularly to producers with populations of herbicide resistant weeds. Incorporating pre-harvest herbicides into the zero-tolerance approach in lentil production may help producers prolong the effectiveness of growing IMI tolerant lentil. By adopting this approach and ensuring that no problem weeds are able to deposit viable seeds into the seed bank, growers would be able to slow the spread of these weeds in their fields. As seeds can persist in the soil for multiple seasons, any approach that can reduce the number of viable seeds would be beneficial for future growing seasons (Bell and Tranel 2010). However, the effect of pre-harvest herbicides on weed seed production and viability has been inconsistent. Timing, weed stage, and species all influence the effectiveness of pre-harvest herbicides on reducing weed seed production. Bennett and Shaw (2000b) observed that pitted morningglory (*Ipomoea lacunose* L.) had matured by the time the pre-harvest herbicides were applied in one of the two site-years. Such variability in weed maturity produced variable results with regard to decreasing weed seed viability with the weeds.

Understanding characteristics such as germination rate, time to maturity, and the growth habits of each weed and crop is important in determining how effective desiccation will be at reducing the quality of weed seed production. Therefore, the objective of this research was to determine the effectiveness of several herbicides applied as pre-harvest herbicides in reducing weed seed viability and vigour of Group 2 resistant *juncea* and kochia in lentil.

4.2 Hypothesis

Glyphosate applied alone at the 900 g a.e. ha^{-1} rate will have a most significant effect on reducing seed viability and vigour of both kochia and *juncea* compared to the contact herbicides in this study.

4.3 Material and Methods

4.3.1 Weed Seed Material

Kochia and imidazolinone-tolerant *Brassica juncea* L. seed was sourced as described in Chapter 3. The field experiment consisted of eighteen pre-harvest herbicide treatments foliar applied to lentil at 30% seed moisture content. There were five contact herbicides (flumioxazin, saflufenacil, pyraflufen-ethyl, glufosinate and diquat) applied alone or tank-mixed with two rates of glyphosate (450, 900 g a.e. ha^{-1}). A summary of these treatments is listed in Table 3.1 in chapter 3 of this thesis. Weed seeds were separated from the harvested lentil samples and stored in paper bags at room temperature until germination and vigour tests were conducted in growth cabinets. Each treatment from the desiccation trial was subjected to vigour and viability tests to determine the effectiveness of the different herbicides at reducing the vigour and viability of the collected weed seeds.

4.3.2 Experimental Design

Two separate experiments were conducted between May and December 2014 using the kochia and *juncea* seed from the field trials described in Chapter 3. Each of the experiments was arranged as a randomized complete block design. The viability experiment was conducted in a growth cabinet, while the emergence experiment was conducted in a growth chamber, both at the University of Saskatchewan. The length of each experiment was 14 days (Table 3.1). Each of the two experiments was run once per site-year for a total of five site-years per each experiment. The objective of the viability experiment was to determine the effect of several pre-harvest herbicides on the viability of the offspring of treated weeds. The vigour experiment was conducted to determine if the pre-harvest herbicide treatments affected the initial competitiveness and seedling vigour of the treated weed seeds. Seedling vigour was assessed by examining the effect on seedling emergence of deep planting and cold temperatures.

The objective of these experiments is to identify pre-harvest herbicides that will either reduce the number of viable weed weeds and or reduce the vigour of these treated weed seeds. Both experiments were run conjointly for each site-year. Environmental conditions for each experiment can be found in Table 4.1.

4.3.3 Experimental Procedure

4.3.3.1 Viability Experiments

One hundred cleaned weed seeds of kochia or *juncea* from each treatment collected from the prior experiment were placed upon two layers of filter paper in moistened (distilled water) 9-cm petri dishes. Each petri dish was placed on trays and put into a growth cabinet. The trays were placed on racks in the growth cabinet at 16^{o} and 90% humidity for 14 days (Table 4.1). Seeds were considered germinated when radicle emergence was greater than 1 mm for both weed species (Horak and Sweat 1994; Webster et al. 2003). Germinated seeds were counted every day until the completion of the experiment. Petri dishes were re-moistened during germination counts. At the end of the experiment, the number of seeds germinated was determined. All seeds that produced a normally formed radicle were considered germinated. The seeds from each treatment that were not germinated were subjected to a viability test using tetrazolium chloride. Tetrazolium provides a quick method to determine viable seeds by staining respiring tissues red (Sawma and Mohler 2002). Tetrazolium testing was performed following the methods discussed in Sawma and Mohler (2002). In this study no seeds were found to have remained dormant and ungerminated.

4.3.3.2Vigour

Twenty-five seeds of kochia or *juncea* from each treatment were seeded into pots measuring 15 cm by 18 cm. *Juncea* seeds were planted 5 cm deep while kochia was planted at a 2.5 cm depth. Two seeding instruments were used to ensure both even distribution and correct depth of seeds. The seeding instruments consisted of a thin platform with evenly spaced nails pushed through either 5 or 2.5 cm from the base of the platform. Each pot was filled with soil to a standard depth across all pots. The seeding instrument was then used to create 25 holes across the soil surface. One kochia or *juncea* seed was then placed in each hole. To cover the seeds the soil surface was gently disrupted to fill all the holes without disturbing the seeds. Watering occurred every second day to ensure the soil remained moist. The growth chamber was set for day length periods of 16 hours and a temperature of 10°C to mimic spring seeding conditions in Saskatchewan. Emergence was counted daily, and the experiment was run for 14 days. Plants were considered emerged as soon as the seedlings were visible. At the end of the experiment, the above ground biomass was collected and placed into an oven at 40°C for 48 hours then weighed.

The seeding depth for the weeds in this experiment was used to help determine if the treatments were affecting the vigour of the weeds. While weed seeds exposed to herbicide treatments may still be viable, they could be injured, or have reduced vigour compared to the non-treated seeds.

4.3.4 Statistical Analysis

Data were analyzed using the PROC MIXED procedure in SAS (SAS Inst. 2014). The assumptions of analysis of variance (ANOVA; homogeneous variance and normal distribution) were evaluated using PROC UNIVARIATE, Levene’s test and the Shapiro-Wilk normality test (SAS Inst. 2014). Herbicide treatment was considered a fixed effect with the

Table 4.1 Experiment locations, start and completion dates, daylight ratio (hours), and temperatures for each site-year experiment at the University of Saskatchewan in 2014.

Year of Field Experiment	Location of Field Experiment	Growth Cabinet Seeding Date	Termination Date	Daylight Ratio (day/night) hours	Temperature (day/night) °C (Cabinet)	Temperature (day/night) °C (Phytotron)
2012	Saskatoon	May14, 2014	May 28, 2014	16/8	16/16	10/10
2013	Saskatoon	June 11, 2014	June 25, 2014	16/8	16/16	10/10
2013	Scott	July 9, 2014	July 23, 2014	16/8	16/16	10/10
2014	Saskatoon	October 1, 2014	October 15, 2014	16/8	16/16	10/10
2014	Scott	October 29, 2014	November 12, 2014	16/8	16/16	10/10

the replication and interaction with herbicide treatment considered random effects. Data transformations were used when the residuals did not meet the assumptions for ANOVA. All data was back transformed for the presentation of results. The COVTEST option in PROC Mixed was used with site-year as a random effect, and when interactions of site-year with fixed factors were significant, it was decided to analyze them separately (SAS Inst., 2014).

Non-linear regression was used to analyze both the germination and seedling emergence timings from both the vigour and viability experiments. Germination and emergence timings were converted into growing degree days (GDH) and analyzed as a general linear model. Timings in each experiment were converted into growing degree days in order to determine the time to 50% germination or emergence. Emergence time was determined using the following equation:

$$Pt = \frac{1}{[1 + e^{a(-t+B)}]}$$

where Pt is the proportion of seeds emerging at time *t*, *t* is thermal time in GDH (base temperature = 0^{o}C) accumulated since the initiation of the experiment, *a* is the estimated rate of emergence (number of emerged seeds per GDH), and *B* is the estimated median emergence time (GDH) in each experimental unit.

Growing degree days were calculated as:

$$GDD = \sum \left[\frac{(Tmax + Tmin)}{2}\right] - Tbase$$

$$GDD = GDH * \text{Hours After Emergence}$$

where Tmax is the daily maximum air temperature, Tmin is the daily minimum air temperature, and Tbase is the base temperature (0°C) for growth. Final emergence, final germination, median germination, median emergence, and biomass were subjected to analysis of variance, combined over replicates, using PROC Mixed (Littel et al. 1996). Means were separated using Tukey's honest significant difference with treatment differences declared significant at $P \leq 0.05$. Means grouping was done using letters to separate treatments and was created using the PDMIX800 macro in SAS (Saxton, 1998). Specific comparisons of interest were made between treatments using single degree of freedom contrasts.

4.4 Results and Discussion

4.4.1 Viability of Kochia and *B. juncea* Progeny Treated by Several Pre-Harvest Herbicides

Pre-harvest applications of herbicides had variable effects on the germination timing and the final germination percentage of kochia and *juncea* seeds (Table 4.2). Except for the kochia time to 50% germination (EG_{50}), there were no significant interactions between the site-year and herbicide treatment and thus, kochia germination time was analyzed within site-years. *Juncea* EG_{50} and both the kochia and *juncea* final germination percentages were combined across site-years (Table 4.2).

Table 4.2 P-values derived from analysis of variance of weed germination showing fixed factors combinations at Saskatoon and Scott, Saskatchewan in 2012-2014.

Source	Kochia EG_{50}	*Juncea* EG_{50}	Kochia Germination	*Juncea* Germination
			P values	
Site-Year	0.1605	0.0615	0.319	0.1895
Herbicide	0.0366*	0.0003***	0.1323	<.0001***
(Site-Year)(Herbicide)	0.0103*	0.0968	0.1159	0.5413

*, **, ***, significant at the 0.05, 0.01, and 0.001 probability levels, respectively

Time to 50% germination for kochia was significantly affected by the herbicide treatment in seeds collected from the Saskatoon site in 2012 and at Scott in 2013 and 2014 (Table 4.3). At Saskatoon in 2012, only glyphosate applied at the full rate (900 g a.e. ha^{-1}) and glufosinate (600 g a.i. ha^{-1}) applied alone and in combination with a half rate of glyphosate (450 g a.e. ha^{-1}) significantly increased the time to EG_{50} by 211, 235, and 221 GDH, respectively. Contrasts showed that glyphosate alone at the 900 g a.e. ha^{-1} rate was more effective at increasing time to 50% germination compare to tank mixes (Table 4.3).

A similar trend was observed in Scott 2013, where glyphosate alone at the 900 g a.e. ha^{-1} rate significantly increased time to 50% germination by 41 GDH compared to tank mixes (Table

4.3). During the same site-year, glufosinate alone increased EG_{50} by 77 GDH compared to the untreated check. Time to EG_{50} further increased by 91 GDH with glufosinate, with a half rate of glyphosate and 103 GDH with glufosinate tank mixed with a full rate of glyphosate. In addition, diquat alone and with a half rate of glyphosate, increased the EG_{50} by 70 and 86 GDH and pyraflufen tank-mixed with both rates of glyphosate increased by 82 and 106 GDH, respectively.

At Scott in 2014, glufosinate with a high rate of glyphosate had significantly higher time to 50% germination than pyraflufen alone, and flumioxazin with both rates of glyphosate (Table 4.3). However, none of these treatments differed significantly from the untreated check. In 2014, at the Saskatoon location, no treatments significantly decreased germination rate. However, contrasts showed that glyphosate (900 g a.e. ha^{-1}) alone increased kochia germination time compared to the contact herbicides alone. This was true in all site-years with the exception of Saskatoon in 2013 (Table 4.3). Treatments with flumioxazin and saflufenacil did not significantly affect EG_{50} from treatments applied at any site-year. Analysis of the final germination percentages revealed that there were no significant treatment and site-year interactions, nor were there interactions between final kochia germination and the herbicide treatments in this study.

Increasing the germination time of weed seeds may have a positive effect on reducing the fecundity of the weeds by delaying the establishment of the weeds until after the crop is established. The weed free period of lentil is from 5 nodes to 10 nodes and Fedoruk (2011) found an inverse relationship between weed biomass and lentil biomass, which could suggest that the longer weeds take to establish in lentil, the fewer seed they will produce. Reducing the competitiveness of weeds such as kochia or wild mustard means that the weeds will compete less with the crop, which will in turn reduce weed seed shed and future weed populations. Kochia, for example, has the ability to regrow after harvest and can deposit up to 5,710 seeds per plant before winter in wheat crops (Mickelson et al. 2004). This late seed bank deposit could prove costly for a producer that is planning on seeding lentil the following year. A pre-harvest herbicide could eliminate that seed shed or at least reduce the vigour of treated seedlings. Increased germination time may allow for a frost to kill the kochia prior to seed set in the fall, or reduce the germination, emergence, and vigour of treated kochia seeds that germinate in the spring. Increased germination time of weeds would also allow the crop to become larger and more competitive prior to competing with the weeds.

The EG_{50} of *juncea* was significantly affected by all treatments, without any significant site-year by herbicide interactions (Table 4.2 and Table 4.4). While there are significant treatment differences, only saflufenacil alone, glufosinate alone, and glufosinate + glyphosate (450 g a.e. ha^{-1}) increased the time to 50% germination by 31, 24, and 26 GDH, respectively. Contrasts highlight that glyphosate at the 450 g a.e. ha^{-1} applied alone was not as effective at increasing the mean germination time of kochia compared to the contact herbicides applied alone or the contact herbicides tank-mixed with glyphosate at the 450 g a.e. ha^{-1}. However, a 900 g a.e. ha^{-1} rate of glyphosate contrasted against the contact herbicides was effective at increasing the mean germination time in all the site-years except Saskatoon in 2013. At Saskatoon in 2012, the greatest difference between the full rate of glyphosate and the contact herbicides was observed with glyphosate increasing median germination time by 158 GDH. This increase in the time to 50% germination by the 900 g a.e ha^{-1} rate of glyphosate in comparison to the contact herbicides suggests that glyphosate was more effective at increasing median germination compared with the tank mix combinations.

Final germination percentage for kochia was not significantly affected by herbicide treatments, despite the significant treatment effects on germination time. However, final germination percentage for *juncea* was significantly affected by herbicide treatments. While the treatment differences were minimal, both rates of glyphosate alone reduced by approximately 3% the final germination compared to the untreated check. The only other herbicides that significantly reduced final germination were diquat applied alone and flumioxazin tank-mixed with glyphosate (450 g a.e. ha^{-1}).

Contrasts showed that glyphosate applied alone at either rate was more effective at reducing final germination percentage for *juncea* compared to the contact herbicides applied alone or in combination with either glyphosate rate (Table 4.4). This suggests that in mustard, the fast-acting activity of the glufosinate impeded the ability of the slower acting glyphosate to move beyond the leaf and into the rest of the plant (Chuah et al.2008; Kudsk and Mathiassen 2004). Conversely, in lamb's quarters (*Chenopodium album* L.), several studies have found that the addition of glufosinate is additive with no or trace antagonism, which suggests that tank-mixing antagonism can be specific to the species of weed (Besancon et al. 2018; Bethke et al. 2013; Chuah et al. 2008; Kudsk and Mathiassen 2004). These studies are in agreement with our study wherein there were greater treatment differences with regard to kochia compared to mustard. The antagonism between the contact treatments and glyphosate is supported by the contrasts, which showed glyphosate applied alone was significantly better at reducing *juncea* germination compared to the contact herbicides applied alone or in combination with glyphosate.

Table 4.3 Mean comparisons of kochia EG_{50} germination time at Saskatoon and Scott, SK from 2012 to 2014. Estimate statements represent differences between herbicide treatments kochia desiccation.

Herbicide	Rate	Kochia EG_{50} Germination Time in Growing Degree Hours				
		Saskatoon 2012	Saskatoon 2013	Saskatoon 2014	Scott 2013	Scott 2014
	(g a.i./a.e. ha^{-1})	Thermal Hours				
Untreated	0	1049 D	941	900	917 DE	955 AB
Glyphosate	450	1003 B-D	977	941	965 A-D	994 AB
Glyphosate	900	1260 A-C	1027	1015	1030 A	1044AB
Pyraflufen-ethyl‡	20	1176 D	948	871	888 E	931 B
Pyraflufen-ethyl + Glyphosate‡	20 + 450	1087 A-D	998	982	998 A-C	1044AB
Pyraflufen-ethyl + Glyphosate‡	20 + 900	1049 A-D	1020	965	1022 AB	1034 AB
Glufosinate	600	1284 A	1070	998	994 A-C	986 AB
Glufosinate + Glyphosate	600 + 450	1270 AB	1020	982	1008 A-C	1039 AB
Glufosinate + Glyphosate	600 + 900	977 D	1008	938	1020 AB	1087 A
Flumioxazin¶	210	936 A-D	1015	1001	974 A-D	989 AB
Flumioxazin + Glyphosate¶	210 + 450	1025 A-D	984	922	948 C-E	941 B
Flumioxazin + Glyphosate¶	210 + 900	1186 A-D	989	979	965 A-D	943 B
Saflufenacil§	50	967 A-D	1027	955	972 A-D	998 AB
Saflufenacil + Glyphosate†	36 + 450	989 CD	1008	936	965 B-D	994 AB
Saflufenacil + Glyphosate†	36 + 900	1130 A-D	962	941	967 A-D	958 AB
Diquat¶¶	415	1142 A-D	1025	943	986 A-C	1003 AB
Diquat +Glyphosate¶¶	415 + 450	1044 A-D	1018	955	1003 A-C	1022 AB
Diquat +Glyphosate¶¶	415 + 900	1046 A-D	958	960	967 A-D	962 AB
Estimates						
Glyphosate (low) vs. TMa (low)		-82	-29	-14	-19	-14
Glyphosate (high) vs. TMa (high)		182**	43	58	41*	48
Glyphosate (low) vs. Contact		-98	-41	-12	24	12
Glyphosate (high) vs. Contact		158**	19	60*	67***	62*
TMa (low) vs. TMa (high)		5	10	0	-5	12

*, **, *** , significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

†† Means within a column followed by the same letter are not significantly different on the basis of $HSD_{0.05}$. TMa denotes tank mix partners.

‡ Merge® at 1% v/v was added in pyraflufen-ethyl and the tank mixture of pyraflufen+glyphosate treatment.

¶ Agral 90® at 0.25% v/v was added in flumioxazin treatment and the tank mixture of flumioxazin+glyphosate treatment.

§ Merge® at 1 L ha^{-1} was added in saflufenacil treatment.

¶¶ Agral 90® at 0.1% v/v was added in diquat and the tank mixture of diquat+glyphosate treatment

Table 4.4 Mean comparisons of *B. juncea* EG_{50} germination time, final germination percent, and kochia final germination percent at Saskatoon and Scott, SK from 2012 to 2014. Estimate statements represent differences between herbicide treatments.

Herbicide	Rate	Final Kochia Germination	*Juncea* Germination EG_{50}	Final *Juncea* Germination
	(g a.i./a.e. ha^{-1})	%	Thermal Hours	%
Untreated	0	89	770 D	94 A-E
Glyphosate	450	90	770 CD	91 H
Glyphosate	900	90	792 A-D	91 GH
Pyraflufen-ethyl‡	20	90	785 A-D	92 E-H
Pyraflufen-ethyl + Glyphosate‡	20 + 450	91	787 A-D	93 B-F
Pyraflufen-ethyl + Glyphosate‡	20 + 900	91	780 A-D	95 A
Glufosinate	600	88	794 A-C	94 A-C
Glufosinate + Glyphosate	600 + 450	90	797 AB	95 A
Glufosinate + Glyphosate	600 + 900	90	785 A-D	93 B-F
Flumioxazin¶	210	90	785A-D	94 A-D
Flumioxazin + Glyphosate¶	210 + 450	90	782 A-D	92 F-H
Flumioxazin + Glyphosate¶	210 + 900	90	775 B-D	94 A-D
Saflufenacil§	50	90	802 A	94 A-D
Saflufenacil + Glyphosate†	36 + 450	90	780 A-D	94 A-D
Saflufenacil + Glyphosate†	36 + 900	90	780 A-D	95 AB
Diquat¶¶	415	90	794 A-D	92 F-H
Diquat +Glyphosate¶¶	415 + 450	89	787 A-D	93 D-G
Diquat +Glyphosate¶¶	415 + 900	90	784 A-D	93 C-G
Estimates				
Glyphosate (low) vs. TMa (low)		-0.29	-16**	-2.53***
Glyphosate (high) vs. TMa (high)		-0.02	11*	-2.57***
Glyphosate (low) vs. Contact		-0.05	21***	-2.52***
Glyphosate (high) vs. Contact		0.12	1	-2.02***
TMa (low) vs. TMa (high)		0.1	6	-0.55**

*, **, ***, significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

†† Means within a column followed by the same letter are not significantly different on the basis of $HSD_{0.05}$. TMa denotes tank mix partners.

‡ Merge® at 1% v/v was added in pyraflufen-ethyl and the tank mixture of pyraflufen+glyphosate treatment.

¶ Agral 90® at 0.25% v/v was added in flumioxazin treatment and the tank mixture of flumioxazin+glyphosate treatment.

§ Merge® at 1 L ha^{-1} was added in saflufenacil treatment.

¶¶ Agral 90® at 0.1% v/v was added in diquat and the tank mixture of diquat+glyphosate treatment

4.4.2 Vigour of Kochia and *B. juncea* Offspring Treated by Several Pre-Harvest Herbicides

Kochia emergence and vigour were significantly affected by the application of pre-harvest herbicides (Table 4.6). Kochia final emergence percentage, time to 50% emergence and final biomass were all significantly affected by the pre-harvest herbicides ($P<0.0001$) (Table 4.5). *Juncea* emergence was not affected with treatments having no significant effect on the emergence rates, time to 50% emergence, or above ground biomass (Table 4.5).

The time to 50% emergence (ET_{50}) for kochia increased with glyphosate (900 g a.e. ha^{-1}) 197 GDH over the untreated check (Table 4.6). The tank mix of diquat (415 g a.e. ha^{-1}) + glyphosate (900 g a.e. ha^{-1}) also significantly lengthened the time to 50% emergence by 7.9 GDH. Flumioxazin (210 g a.e. ha^{-1}) + glyphosate (900 g a.e. ha^{-1}) increased ET_{50} of kochia seed from 81.0 to 87.6 GDH. In addition, glufosinate alone (600 g a.e. ha^{-1}) and with the half rate of glyphosate (450 g a.e. ha^{-1}) increased the time to ET_{50} by 9.6 and 9.5 GDH, respectively. There were, however, no significant differences amongst these treatments, only between the aforementioned treatments and the untreated check (Table 4.6).

Contrasts did not indicate any significant differences between glyphosate applied alone compared to all the other treatments. However, glyphosate applied at the full rate resulted in the greatest numerical increase in time to 50% emergence over all other treatments (Table 4.6). While *juncea* emergence timing was not significantly impacted by the treatments, contrast comparisons demonstrate that glyphosate applied alone at a full rate resulted in the time to 50% emergence increasing by 36 GDH compared to either the contact herbicides applied alone and 43 GDH compared to the tank-mix (Table 4.7). This suggests that at the time of application, most of the seeds were either too mature to be affected or were less susceptible to pre-harvest herbicides compared to kochia. Nevertheless, with the increased median emergence times observed, it does appear that glyphosate may be translocating to the seed in small amounts.

Final emergence of kochia was affected by most herbicides, but there were no differences in *juncea* final emergence percentages (Table 4.7). Both glyphosate treatments reduced final kochia emergence by 71% and 80% compared to the untreated check. Pyraflufen applied alone did not significantly reduce final emergence, but when tank-mixed with glyphosate final emergence was reduced by 60 to 66% at the half and full rate, respectively. Surprisingly, glufosinate treatments had the greatest impact on kochia emergence. A full rate of glyphosate tank-mixed with glufosinate reduced final emergence by 88%,

Table 4.5 P-values derived from analysis of variance of weed emergence showing fixed factors combinations at Saskatoon and Scott, Saskatchewan in 2012-2014.

Site-year	Kochia ET_{50}	*Juncea* ET_{50}	Kochia Emergence %	*Juncea* Emergence %	*Juncea* Biomass	Kochia Biomass
			P-values			
Site_year	0.3798	0.3477	0.2175	0.2760	0.4163	0.2093
Herbicide	<.0001***	0.2519	<.0001***	0.3281	0.3450	<.0001***
(Site_year) (Herbicide)	0.0571	0.3317	0.4783	0.0330*$^{\alpha}$	0.0623	0.4585

*, **, ***, significant at the 0.05, 0.01, and 0.001 probability levels, respectively
α signifies relationship is not over 10% of total covariance parameters

while glufosinate applied alone reduced emergence by 80%. Glufosinate and the half rate of glyphosate tank-mix was the least effective, but still reduced the kochia emergence rate by 73%. Applications of flumioxazin and saflufenacil also reduced kochia emergence relative to the untreated check. Tank mix combinations of flumioxazin or saflufenacil with either rate of glyphosate did not significantly reduce the final emergence of kochia. Diquat applied alone had no direct impact on kochia emergence, but tank-mixes with glyphosate reduced emergence by 63-77%. Contrasts showed that a full rate of glyphosate resulted in lower kochia emergence (14%) compared to the contact herbicides applied alone (Table 4.6).

Kochia seedling biomass was significantly impacted by all treatments (Table 4.6). While every treatment showed a numerical biomass reduction compared to the untreated check, not all reductions were significant and there was a great amount of variation among treatments (Table 4.5). Overall glyphosate and glufosinate had the greatest impact on kochia biomass with glyphosate (900 g a.e. ha^{-1}) and glufosinate reducing mean biomass by 60 and 61 mg/pot, respectively. Saflufenacil applied alone, saflufenacil + glyphosate (900 g a.e. ha^{-1}), diquat + glyphosate (450 g a.e. ha^{-1}), and diquat + glyphosate (900 g a.e. ha^{-1}) were intermediate, and flumioxazin and pyraflufen had no significant impact on kochia biomass. Contrasts showed that the full rate of glyphosate applied alone was slightly more effective at reducing kochia biomass compared to all other treatments (Table 4.6). For *juncea* biomass, the contrasts show that the tank-mix with a half rate of glyphosate was slightly more effective at reducing biomass compared to a full rate tank-mix of glyphosate (Table 4.7).

Table 4.6 Mean comparisons of kochia seed time to 50% emergence, final emergence percentage, and plant biomass using seed collected from pre-harvest herbicide studies conducted at Saskatoon and Scott, SK from 2012 to 2014. Estimate statements represent pre-planned comparisons between glyphosate rates, glyphosate with contact herbicides, and tank-mix rates.

Herbicide	Rate	ET_{50} Emergence	Final Emergence	Above-ground Biomass
	(g a.i./a.e. ha^{-1})	Thermal Hours	%	g
Untreated	0	1944 C	44.5 A	74 A
Glyphosate	450	2081 A-C	12.7 BC	27 A-D
Glyphosate	900	2141 AB	9.1 BC	14 CD
Pyraflufen-ethyl‡	20	2030 A-C	24.4 AB	50 A-C
Pyraflufen-ethyl + Glyphosate‡	20 + 450	2021 A-C	15.1 BC	29 A-D
Pyraflufen-ethyl + Glyphosate‡	20 + 900	2050 A-C	17.4 BC	27 A-D
Glufosinate	600	2174 A	6.3 C	13 CD
Glufosinate + Glyphosate	600 + 450	2172 A	13.2 BC	25 B-D
Glufosinate + Glyphosate	600 + 900	2088 A-C	5.0 C	8 D
Flumioxazin¶	210	2033 A-C	17.8 BC	31 A-D
Flumioxazin + Glyphosate¶	210 + 450	2047 A-C	17.2 BC	34 A-D
Flumioxazin + Glyphosate¶	210 + 900	2102 AB	19.4 BC	44 A-C
Saflufenacil§	50	2088 A-C	10.1 BC	20 B-D
Saflufenacil + Glyphosate†	36 + 450	2083 A-C	19.3 BC	36 A-D
Saflufenacil + Glyphosate†	36 + 900	2050 A-C	11.3 BC	22 B-D
Diquat¶¶	415	1980 BC	26.6 AB	61 AB
Diquat +Glyphosate¶¶	415 + 450	2090 A-C	9.9 BC	23 B-D
Diquat +Glyphosate¶¶	415 + 900	2134 AB	16.3 BC	24 B-D
Estimates				
Glyphosate (low) vs. TM[a] (low)		0	-1.7	-0.01
Glyphosate (high) vs. TM[a] (high)		55	-5.6	-0.03
Glyphosate (low) vs. Contact		22	-2.9	-0.02
Glyphosate (high) vs. Contact		79	-6.3*	-0.06*
TM[a] (low) vs. TM[a] (high)		0	-0.5	0.02

*, **,*** , significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
†† Means within a column followed by the same letter are not significantly different on the basis of $HSD_{0.05}$.
TMa denotes tank mix partners.
‡ Merge® at 1% v/v was added in pyraflufen-ethyl and the tank mixture of pyraflufen+glyphosate treatment.
¶ Agral 90® at 0.25% v/v was added in flumioxazin treatment and the tank mixture of flumioxazin+glyphosate treatment.
§ Merge® at 1 L ha-1 was added in saflufenacil treatment.
¶¶ Agral 90® at 0.1% v/v was added in diquat and the tank mixture of diquat+glyphosate treatment

Table 4.7 Mean comparisons of *B. juncea* seed vigour using seed collected from pre-harvest herbicide studies conducted at Saskatoon and Scott, SK from 2012 to 2014. Estimate statements represent pre-planned comparisons between glyphosate rates, glyphosate with contact herbicides, and tank-mix rates.

Herbicide	Rate	ET_{50} Emergence	Final Emergence	Above-ground Biomass
	(g a.i./a.e. ha^{-1})	Thermal Hours	%	g
Untreated	0	2362	65	1.35
Glyphosate	450	2381	69	1.36
Glyphosate	900	2402	67	1.33
Pyraflufen-ethyl‡	20	2345	63	1.17
Pyraflufen-ethyl + Glyphosate‡	20 + 450	2362	66	1.37
Pyraflufen-ethyl + Glyphosate‡	20 + 900	2359	66	1.39
Glufosinate	600	2357	66	1.43
Glufosinate + Glyphosate	600 + 450	2383	63	1.32
Glufosinate + Glyphosate	600 + 900	2364	67	1.34
Flumioxazin¶	210	2371	65	1.48
Flumioxazin + Glyphosate¶	210 + 450	2374	62	1.30
Flumioxazin + Glyphosate¶	210 + 900	2342	70	1.47
Saflufenacil§	50	2378	68	1.35
Saflufenacil + Glyphosate†	36 + 450	2376	64	1.26
Saflufenacil + Glyphosate†	36 + 900	2357	64	1.42
Diquat¶¶	415	2386	70	1.44
Diquat +Glyphosate¶¶	415 + 450	2374	58	1.15
Diquat +Glyphosate¶¶	415 + 900	2376	68	1.47
Estimates				
Glyphosate (low) vs. TM[a] (low)		7	6.2*	0.08
Glyphosate (high) vs. TM[a] (high)		43**	0.2	-0.09
Glyphosate (low) vs. Contact		12	2.3	-0.02
Glyphosate (high) vs. Contact		36**	0.7	-0.04
TM[a] (low) vs. TM[a] (high)		14	-4.4*	-0.14**

*, **, ***, significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
†† Means within a column followed by the same letter are not significantly different on the basis of $HSD_{0.05}$.
TMa denotes tank mix partners.
‡ Merge® at 1% v/v was added in pyraflufen-ethyl and the tank mixture of pyraflufen+glyphosate treatment.
¶ Agral 90® at 0.25% v/v was added in flumioxazin treatment and the tank mixture of flumioxazin+glyphosate treatment.
§ Merge® at 1 L ha^{-1} was added in saflufenacil treatment.
¶¶ Agral 90® at 0.1% v/v was added in diquat and the tank mixture of diquat+glyphosate treatment

The results of this experiment showed that median emergence time of kochia was generally influenced by several pre-harvest herbicides, most notably glyphosate. Similar results have been reported in other desiccation or late-season herbicide application studies. Steadman et al. (2006) reported that when herbicides were applied between late milk and soft dough stage, coleoptile and radicle growth rates of annual rye grass (*Lolium rigidum* L.) were reduced by applications of glyphosate (450 g a.e. ha^{-1}) or a tank-mix combination of paraquat (135 g a.i. ha^{-1}) and diquat (115 g a.i. ha^{-1}). While there was no effect on seedling growth rate, application timing did influence total seed viability (Steadman et al. 2006). In contrast, the results of the current study showed that desiccation treatments had no significant effect on the median emergence time of *juncea*. This has also been noted in other studies. For example, Kumar and Jha (2015) concluded that a post-harvest application of dicamba alone or tank-mixed with 2,4-D, atrazine, or diflufenzopyr when kochia was in the early bloom stage did not impact the competitive ability of kochia seedlings the following season. The results of these studies, along with the current work, demonstrate that herbicide application can lead to variable results on weed seed viability and seedling competitiveness.

Final seedling emergence percentage of kochia was also impacted by herbicide treatments, but there was no impact on *juncea* seedlings. Variable responses of different weed species to herbicide application have been noted in literature. Jha and Norsworthy (2012) reported that glyphosate and glufosinate reduced seedling emergence when applied to palmar amaranth (*Amaranthus palmeri L.*) as a late-season herbicide. In contrast, Taylor and Oliver (1997) found that regardless of herbicide, rate, or application timing, over 90 percent of the treated sicklepod (*Senna obtusifolia* L.) seeds remained viable when pre-harvest herbicides were applied to control sicklepod in soybean. In their study the weed stage was consistently more advanced than the crop stage, which resulted in reduced efficacy on weed seeds compared to other studies such as Isaacs et al. (1989) or Ratnayake and Shaw (1992).

In this study kochia generally exhibited low final germination, which was likely due to the deep seeding and the low temperatures the experimental treatments provided. The temperature in this experiment was set at 10°C to further impact and stress the seeds. Lentil can be planted in Saskatchewan when the soil temperature, at the depth of seeding, is as low as 5°C. The weeds that emerge before or near the time of the lentil crop will be the most damaging to the yield and have the best chance to produce viable offspring prior to the application of pre-harvest herbicides. Measuring the vigour of kochia and *juncea* in these spring-like conditions similar to when lentil will be seeded provides insight into how these weeds will behave in a field setting.

In the current study both weed species were well past the inflorescence stage at herbicide application timing, with *juncea* maturity generally further advanced physiologically than kochia. Several studies agree that herbicide applications made when weed seeds are in early development, and are still receiving resources from the plant, have a greater ability to reduce weed seed production, along with vigour and viability (Isaacs et al. 1989; Bennett and Shaw 2000b). In soybean, chlorimuron and imazaquin applied at the late fruit stage of sicklepod (*Cassia obtusifolia* L.) had mixed results in reducing seed production and viability (Isaacs et al. 1989). The most significant and consistent reductions in seed production and viability came from herbicide applications at the early bloom stage and early fruit stages of sicklepod, and with no significant differences occurring at the late fruit stage (Isaacs et al. 1989).

While pre-harvest herbicides may not entirely prevent weed seed production, reducing the vigour of the future offspring is still an important part of managing weed populations in a field. This study has found that several of the treatments resulted in significantly less viable kochia seedlings and those that did emerge did so more slowly than the untreated check. Having a greater understanding of how pre-harvest herbicides affect seed shed and the next generation of weeds is an important component of understanding how to incorporate an effective weed management program on farm (Korres et al. 2018). Less vigorous weeds may not possess the ability to emerge from the soil, establish themselves and compete with a crop for light and nutrients. Reducing the number of weeds that will be able to produce offspring can both reduce future weed pressure as well as reduce the chance of weeds developing herbicide resistance (Norris 2003; Neve et al. 2011). Minimizing the likelihood of the development of resistance could help lentil producers save money by reducing lentil yield loss from kochia or delaying the onset of further herbicide resistance by minimizing the population of seeds in the seedbank (Bagavathiannan and Norsworthy 2012).

For a lentil producer attempting to manage kochia or mustard, a pre-harvest herbicide is most likely going to be applied. A glyphosate and/or glufosinate combination will offer the greatest potential of reducing kochia and mustard seedling emergence in the following field season. When tank-mixing herbicides, there is an added cost to the producer for adding the additional herbicide. The prices below outline an approximate cost of each of the treatments in this study, based on current retail prices. Glyphosate applied at either rate is the least costly pre-harvest option in lentil at either $6.62 or $13.23 per hectare. The contact herbicides are more expensive with glufosinate at $14.46, pyraflufen at $20.00, diquat at $36.00, saflufenacil at $39.00 alone or $29.00 when applied with glyphosate, and flumioxazin at $50.39 per acre. Taking into consideration the price, glufosinate is the least costly of the contact herbicides to apply either alone or with glyphosate.

In the current study, glufosinate and diquat provided the most consistent reduction of kochia seedling biomass compared to diquat, saflufenacil, pyraflufen, and flumioxazin. However, when applied alone, glufosinate and diquat had variable efficacy. Saflufenacil, pyraflufen, and flumioxazin did not provide a consistent reduction of kochia seedling biomass when applied alone. Likewise, these three contact herbicides applied in a tank-mix with glyphosate had little impact and were much less efficacious than glufosinate and diquat. The ability of glyphosate to translocate could help to explain the decreased vigour observed in kochia seedlings from glyphosate applications in the current study. Unlike glyphosate, most contact herbicides do not have the ability to translocate in plant material (Cobb and Reade 2014). Hill et al. (2016) provide results that demonstrate herbicides can provide reduced weed seed production in subsequent field seasons and that weed management is improved when applied at an earlier physiological weed maturity stage. Their results showed that all weed species produced viable seeds when immature seed was present at the time of herbicide application. The reduction in viable weed seed production increased from 64 up to 100% when the herbicide application targeted the immature seed stage compared to terminating weeds at the onset of maturity (Hill et al. 2016). Seedling viability was also reduced in a pre-harvest herbicide study in sicklepod by both glufosinate and paraquat (Ratnayake and Shaw 1992).

Our results show that pre-harvest applications of pyraflufen-ethyl, flumioxazin and saflufenacil had little to no effect on the vigour of weed seedlings and as such, are not an effective choice to reduce weed seed viability. While pyraflufen is a registered herbicide for desiccation in potato (*Solanum tuberosum* L.) it does not have a registration on any other crop in western Canada. Therefore, it does not have enough efficacy on its own to be an effective tool. Likewise, the results we observed with flumioxazin and saflufenacil were also inconsistent and generally required glyphosate if there was any impact on weed emergence and biomass. Although they had little impact in our study, Soltani et al. (2013) noted that both herbicides controlled several weeds when applied as a desiccant in dry edible bean (*Phaseolus vulgaris* L.).

Weed morphology may also affect the efficacy of pre-harvest herbicide treatments. Several studies have found that the earlier pre-harvest herbicide application is made, the more effective it is at reducing the vigour of weed seeds (Isaacs et al. 1989; Clay and Griffin 2000). These studies suggest that earlier applications were more effective at reducing both total weed seed production and viability of the treated weed seeds than later applications. Nevertheless, while later herbicide timings may not affect weed seed production, seedling vigour can be impacted, suggesting that there is a benefit to late-season herbicide applications even if the target weeds are past the stage where the herbicides can effectively reduce total seed set (Isaacs et al. 1989). As such, there are multiple factors to consider when utilizing pre-harvest herbicides to minimize the addition of new weed seeds to the seed bank. Negatively impacting any aspect of weed seed production can ultimately delay germination/emergence and reduce the competitive ability of subsequent weed populations (Bennett and Shaw 2000b).

4.5 Conclusion

In this study, glyphosate was the most effective herbicide at reducing kochia and *juncea* median germination time. Glufosinate, diquat and pyraflufen alone, and tank-mixed with glyphosate provided some reduction in kochia germination vigour, while saflufenacil and flumioxazin had no effect. No treatment was able to consistently reduce kochia germination across all site-years.

The results suggest that growers choose either glyphosate or glufosinate applied alone or in a tank mix to reduce the vigour of kochia. Glyphosate applied alone and tank-mixed with diquat at the full rate will reduce the number of viable *juncea* seeds. However, the extent of the reductions will be a function of environmental conditions and the maturity of mustard and kochia. Any reduction in the vigour of future weeds can render them less competitive and should further reduce future additions to the weed seed bank. It is important to note that while glyphosate is an effective harvest aid, applying glyphosate alone increases the selection pressure for glyphosate resistant weeds. Tank-mix combinations between glyphosate and either glufosinate or diquat may help to slow the spread of resistance development. As both these contact herbicides have different mechanisms of action compared to glyphosate the tank mix of either of these herbicides with glyphosate could both help to slow the spread of glyphosate-resistant kochia and delay the development of glyphosate resistant mustard or any other weeds present at the time of application.

5.0 General Discussion

5.1 The Use of Pre-Harvest Herbicides on Kochia and *B. juncea* in Lentil

The results presented in this thesis demonstrate that pre-harvest herbicides can be effective tools for drying down kochia and *juncea* while also reducing the viability and vigour of the treated weed seeds of both species. Glyphosate, glufosinate, and diquat applied alone or in combination with glyphosate had the greatest impact on drying down kochia and *juncea* (Chapter 3). Lentil yield was not significantly impacted by the treatments. These findings suggest that the application of harvest aids at 30% lentil moisture can have a significant impact on drying down kochia and *juncea* and reducing TSW. The results support the hypothesis that glyphosate tank-mixed with the contact herbicides will increase weed dry-down. None of the treatments significantly reduced seed production compared to the untreated check. Other studies evaluating the effects of harvest aid herbicide applications of weed seed production have also found conflicting results. Glufosinate provided consistent dry-down of several weeds including pitted morningglory and spotted spurge (Ellis et al. 1998, Bennett and Shaw 2000b). Soltani (2013) also found that glyphosate provided good visual control of several weeds, although the addition of glyphosate to the contact herbicides did not significantly speed up dry-down. These authors all found variable control with pre-harvest or late season herbicides due to environmental conditions and weed stage. However, they all indicated that even non-optimal control can still be beneficial in terms of reducing the vigour or weed seed progeny in subsequent crops. The results presented in this thesis are in agreement with these authors, as the reductions in both weed seed production and vigour of the treated weed seeds are important in managing weed seed additions to the seed bank.

In this study, kochia generally was more impacted by the herbicide treatments than was *juncea*. Different weed species have been shown to react differently to the tank mix of glyphosate and glufosinate. In some species there is an antagonistic effect with the tank-mix and in others there is an additive effect (Besancon et al. 2018; Bethke et al. 2013; Chuah et al. 2008; Kudsk and Mathiassen 2004). This data supports our results, where the greatest benefit of tank-mixing glufosinate and glyphosate was associated with kochia, a close relative of lamb's quarters.

Literature suggests that weed stage has a significant impact on the effectiveness of herbicides at reducing weed seed viability (Isaacs et al. 1989; Bennett and Shaw 2000b). In lentil, the earliest pre-harvest herbicides can be applied is at 30% moisture (Saskatchewan Ministry of Agriculture 2018). Currently diquat, saflufenacil, and glyphosate are registered to be applied at this stage (Saskatchewan Ministry of Agriculture 2018). Clay and Griffin (2000) concluded that for glyphosate to reduce common cocklebur (*Xanthium strumarium L.*) seed production and viability, the crop stage needs to coincide with the initial seed set of the weed so that a pre-harvest herbicide can be applied at the correct crop stage and be efficacious. As both mustard and kochia germinate early and grow rapidly, it is important that growers ensure the proper timing of the crop pre-harvest application coincides with that of most sensitive weed stage (prior to seed development). In this study, both the kochia and *juncea* emergence occurred congruently with the lentil emergence. Using an effective, residual pre-seed herbicide, such as pyroxasulfone, may help to synchronize kochia and mustard with pre-harvest herbicide timing by delaying the emergence of the weeds (King and Garcia 2008).

5.2 Management Implications

Reducing weed seed shed and seedling vigour are important aspects of the zero-tolerance threshold (Norsworthy et al. 2014). Of the treatments studied, glyphosate alone at 900 g a.e. ha^{-1} and glufosinate 600 g a.i ha^{-1} provide the most consistent dry-down and reduction in seed production and seedling vigour. Following the zero-tolerance threshold may be the most important strategy in slowing the spread of kochia, particularly glyphosate-resistant kochia. Norsworthy and others have highlighted attributes of palmer amaranth that have led them to conclude that a zero-tolerance threshold is the only pragmatic way to stop the spread of this weed (Bagavathiannan et al. 2013a; Jha and Norsworthy 2009; Norsworthy et al. 2012; Norsworthy et al. 2014). Kochia shares many of these attributes including being highly competitive and prolific. Kochia also has little or no dormancy, meaning that the vast majority of weeds shed in the fall germinate in the following spring. While wild mustard does not share as many characteristics with palmer amaranth as kochia, it also has ALS resistant populations and following a zero-tolerance threshold is the most appropriate way to manage this weed in the field.

Tank-mixing glyphosate with the contact herbicides generally increased the dry-down of plant material but did not significantly reduce seedling vigour compared to the contact herbicides applied alone. Growth stage is an important factor in maximizing the efficacy of the treatments on weeds, as the herbicide treatments cannot be applied earlier than the labeled crop stage in lentil. This indicates that the management and reduction of weeds and weed progeny need to be part of a sustainable system that utilizes a variety of weed control measures. Glyphosate has been noted as the most important herbicide in history (Duke and Powles 2008) and the importance of keeping glyphosate efficacious cannot be overstated for western Canada. Weed seed shed and additions to the seedbank are important factors that can contribute to the development of herbicide resistant weeds. Increases in weed populations through weed seed shed increase the selection pressure of herbicide resistance developing by increasing the size of weed populations.

Although effective, growers need to apply pre-harvest herbicides in a sustainable manner. Tank-mixing herbicides with different mechanisms of action can reduce herbicide selection pressure for resistance. This study explored several herbicide tank mixes with glyphosate on both increasing the harvestability of lentil by drying down kochia and *juncea*, and by using the herbicide treatments to reduce the vigour and the number of viable kochia and mustard seed shed into the seed bank. The addition of glyphosate generally helped reduce straw moisture compared to the contact herbicides alone in both weed species, but there was no benefit with tank-mixing glyphosate with the contact herbicides in reducing viable and vigorous weed seed shed. None of the herbicide treatments were able to reduce weed seed production, though there was success with glyphosate tank-mixes with glufosinate and diquat at reducing the TSW of kochia. This reduction in seed size with the tank-mixes did not translate into consistent reductions in weed seed vigour, and contrasts indicated that glyphosate alone was more successful. This demonstrates that reductions in TSW alone does not necessarily lead to reductions in weed seed vigour and that glyphosate applied alone was the most successful treatment at reducing the vigour of treated kochia seeds.

The results of this study indicate that glyphosate and glufosinate alone were the most consistent pre-harvest herbicides. While tank-mixing these two herbicides would increase grower costs, there are several benefits to tank-mixing glyphosate and glufosinate. Tank-mixing to delay further herbicide resistance development has already been mentioned but reducing chemical residues in the lentil seed would be another important reason for tank-mixing. Research into herbicide residues in lentil has shown that both tank-mixing and herbicide timing are important factors that can impact the amount of herbicide residue in the harvested crop. Applications of glufosinate or diquat with glyphosate produced the most consistent crop dry-down in lentil with acceptable residue levels (Zhang 2016). Pre-harvest timing is also important and as growers typically use visual methods to determine the correct timing mistakes can be made and applications could be applied too early. Early applications of pre-harvest herbicides have been shown to increase residue levels in lentil seed (Zhang 2016).

Although the results of this study are encouraging, the integration of several control measures such as cultural, mechanical, and chemical methods is the only way to successfully and sustainably manage current and future weed populations. In lentil, weed management is integral due to the poor-competitiveness of the crop (Menalled 2010). The use of pre-harvest herbicides should only be viewed as a part of the chemical pillar of IWM. By integrating pre-harvest herbicides in combination with pre-seed, post-emergent, and post-harvest herbicides a lentil producer is likely to have a more significant effect on late-season weed control and can maximize the efficacy of the herbicide component with IWM. Early-season herbicide applications (pre-seed and post-emergent) are important for reducing competition between the crop and weeds. However, without the application of pre-harvest and post-harvest herbicides, escaped weeds have the potential for seed production, thus adding to the seed bank for the following season (Hill et al. 2016).

5.3 Future Research

Kochia and wild mustard continue to pose a significant challenge to the production of lentil and other crops. This thesis has only considered the impact of a single chemical approach of the efficacy of several herbicides applied pre-harvest in lentil. There are several other chemical and non-chemical approaches that could be investigated to determine the impact of a systems approach to reducing or eradicating the addition of mustard and kochia seed to the seed bank. Several studies showed that the earlier the application of a pre-harvest herbicide to weeds, the greater the impact the herbicide has on the reduction of seed development viability (Ratnayake and Shaw 1992; Bennett and Shaw 2000b; Clay and Griffin 2000). Further investigation of the effects of herbicide application timing on maturing kochia and wild mustard would be beneficial in determining the impact of timing of seed production. Moreover, the results may help in determining the most effective herbicide combinations based on weed stage at the pre-harvest lentil timing.

The current study and other studies referenced above have highlighted the importance of application timing based on weed maturity and more specifically, herbicide efficacy and its impact on reducing weed seed production, viability, and vigour. Further research should look at the application timing effects of these herbicides on weeds and weed seed as a function of plant maturity. The results of such a study could provide a greater understanding of how kochia and *juncea* maturity affects the efficacy of pre-harvest herbicides, which may lead to more insights on how best to approach weed control in lentil prior to harvest.

With a chemical approach in IMI-lentil, the use of pre-seed, pre-harvest, post-harvest, and residual herbicides could be used as a system to help control kochia and wild mustard in lentil. Pre-seed herbicides with residual control may help in delaying the emergence and growth of weeds in lentil. In the current study the emergence of lentil and the weeds occurred at the same time, with both kochia and wild mustard growing quickly and out-competing the lentil. Residual herbicides applied pre-seed or pre-emergence may delay the development of the weeds, ensuring that at the pre-harvest timing the weeds are more sensitive to a herbicide application as they may be more immature than they were in this study. Post-harvest herbicides may also provide a control measure for kochia or mustard seeds that germinate and produce seeds after harvest as well as the control of problem perennial weeds in lentil, such as narrow-leaved hawk's beard.

While the use of herbicides in lentil production is important, there are many other control measures that could be beneficial in lentil, particularly in the context of a zero-tolerance approach to weeds. Seeding rate and timing, the use of different lentil cultivars, and mechanical control options have been studied in relation of the impact of weeds in lentil, but the impact of future weed pressure in lentil derived from seedbank inputs has not been considered or investigated to date.

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