Integrated Weed Management in Lentil (*Lens culinaris Medik.)*

A Thesis Submitted to the College of Graduate Studies and Research

In Partial Fulfillment of the Requirements For the Degree of Master of Science In the Department of Plant Sciences

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1 Introduction

Herbicidal weed control has become the preferred method of weed control for farmers in the developed world (Harker and O'Donovan 2013, Walsh and Powles 2007). Use of herbicides has provided producers with simple efficacious weed control and has lead to improved crop yields (Heap 2014a, Walsh and Powles 2007). Although herbicides have many benefits there are also drawbacks to their increased application. Herbicide use has imposed a strong selection pressure for weeds that possess rare mutations and impart resistance to the activity of a herbicide. Repeated use of the same herbicide mode of action results in the creation of a weed population that is no longer controlled by that herbicide mode of action.

Herbicides were first used on the Canadian prairies in the 1940s and quickly earned favour with farmers. Herbicides experienced a 'golden age' in the 1960s and 1970s with many new herbicides and unique mode of actions being brought to market (Holm and Johnson, 2009). However in the last 30 years no herbicides with novel sites of action have been introduced to the global marketplace (Heap 2014b). In addition stricter environmental regulations in many parts of the world have resulted in the deregistration of some existing herbicides. These factors mean that when weed populations become resistant to one or more herbicide MOAs farmers are increasingly without good herbicide options to control these resistant weeds. This situation is now being cited as a serious factor that threatens crop production worldwide (Heap 2014b).

Integrated weed management (IWM) offers an alternative to a system that relies solely on herbicides and therefore IWM systems are less likely to select for herbicide resistance (Blackshaw et al. 2008). Integrated weed management utilizes herbicides in combination with other control strategies including crop competition, mechanical weed control, and crop rotations. By increasing the crops' ability to compete with weeds, reliance on herbicides and selection pressure for herbicide resistance is reduced (Anderson 2000). Integrated weed management systems aim to sustain both the current season profitability, via in-season weed control, as well as future productivity of the farming system, via reduction in both weed seedbank return and selection for herbicide resistant weeds. Despite the fact that integrated weed management systems have been proven effective and championed by respected weed scientists for at least two decades, their adoption by producers has generally been quite low (Doohan et al. 2010).

In western Canada specifically, producers continue to favour herbicides as their primary, and in many cases only, method of weed control. It is estimated that over 500 million dollars is spent annually on herbicides to control wild oat, which is one of the most prevalent herbicide resistant weeds found on the prairies (Leeson et al. 2006, Beckie et al. 2013). A study examining farmers' views of herbicide use and integrated weed management indicated that farmers perceived weeds as having high risk and few benefits while herbicides were perceived to have great benefits and few risks (Doohan et al. 2010). This attitude explains why farmers are willing to spend money applying herbicides while not necessarily considering the risks associated with development of herbicide resistant populations. Despite farmer preference for herbicidal weed control, it is clear the attempts to manage resistance through herbicide management and diversity alone will not be sufficient (Norsworthy et al. 2012). In order to make integrated weed management more attractive and attainable to farmers, integrated weed management strategies should be developed that work well with minimal modification of current farming practices and use weed control strategies that interact favourably with herbicidal weed control.

The case of Group 2 herbicide resistant weeds in Canadian prairie lentil crops represents an ideal model system in which to study the interaction of lentil herbicides with cultural and mechanical weed control practices. Development of an integrated weed management system would greatly benefit lentil producers who have few control options to deal with Group 2 resistant weeds.

This project focused on evaluating methods to control Group 2 herbicide resistant mustard in lentils using integrated strategies that complement herbicide application. This was achieved by conducting two field studies. The objective of the first study was to evaluate an integrated system combining cultural and mechanical practices with application of currently registered herbicides to control wild mustard in lentil. It was hypothesized that by utilizing cultural and mechanical weed control tactics herbicide use can be decreased while still achieving weed control and yields similar to those realized in a system relying solely on herbicides. The objective of the second study was to evaluate the ability of in-crop application of a group 14 herbicide chemistry to control wild mustard when integrated with the cultural practice of increased crop seeding rate. It was hypothesized that by increasing the competitive ability of the lentil crop via increased crop density, herbicide efficacy can be increased. The results of these studies will help determine optimum management of Group 2 resistant wild mustard in lentil using a combination of physical, chemical, and cultural methods. This will allow lentil growers to grow lentils with less yield loss, and on land where they may not have been able to due to herbicide resistant weeds. It will also create an integrated weed management system for lentil that will reduce reliance on herbicide usage and help to delay the onset of herbicide resistance to new herbicide modes of action.

2 Literature Review

2.1 Lentil Background

Lentil (*Lens culinaris* Medik.) is one of humanity's oldest crops and is believed to have first been domesticated and cultivated in the Fertile Crescent of the Near East (Sonnante et al. 2009). Lentil is an important crop in many parts of the world, particularly in parts of Asia and the Mediterranean, where it represents an important human protein source (Sarker and Erskine 2006).

2.2 Lentil Description

Lentils are short in stature compared to most cereal and oilseed crops grown on the Canadian prairies. The varieties currently grown in Saskatchewan range in height from approximately 30 to 45 cm (SSGA 2013). Lentils exhibit a slow growth rate, particularly early in the growing season, with slow canopy closure (Brand et al. 2007, Kirkland et al. 2000) . Thus, the lentil canopy is often sparse early in the season and weeds are able to occupy space in the canopy and compete against the lentil crop for resource acquisition (Elkoca et al. 2005). These factors make lentil a weak competitor against weeds, and weed control is one of the most significant limitations in lentil production worldwide (Brand et al. 2007). Lentil also has an indeterminate growth habit, meaning it continues to flower until experiencing some form of stress. This stress may come in the form of high temperatures or drought, as lentils' relatively shallow root system, estimated at 0.8 m deep, means that it is only moderately resistant to these factors (Gregory 1986).

2.3 Lentil in Saskatchewan

Saskatchewan farmers first grew lentil in 1970 on approximately 600 hectares, and since then lentil acreage has expanded rapidly (McVicar et al. 2010). In 2013 seeded area for lentil in Saskatchewan was estimated at 930 000 ha (SMA 2013a). Lentil has now become an important part of the Saskatchewan farm economy, particularly in the Brown and Dark Brown soil zones where it is best adapted for growth (McVicar et al. 2010). In addition to providing producers with economic returns, lentils are favored by Saskatchewan farmers as they aid in the diversification and lengthening of crop rotations. Lentils' ability to fix its own nitrogen when inoculated with the appropriate Rhizobium strain also reduces the requirements for additions of nitrogen fertilizer. In the 2010-2011 crop year Canada exported 1.1 million tonnes of lentils and Saskatchewan's lentil exports accounted for 97 percent of this tonnage (McVicar et al. 2010).

2.4 Weed Control in Lentil

2.4.1 Yield Loss Due To Weed Competition

Achieving acceptable weed control is one of the biggest challenges faced by prairie lentil growers. Lentils' weak competitive ability begins early in the lifecycle, as they are noted to have poor seedling vigor (Basler 1981). Swanton et al. (1993) evaluated crop yield loss due to weeds and found that in both Saskatchewan and Manitoba, lentil suffered that greatest percentage yield loss due to weeds of all crops studied. Yield losses in lentil due to weed competition have been estimated at between 25 and 80% (Ball et al. 1997, Boerboom and Young 1995, Swanton et al. 1993). Farmers have traditionally struggled with achieving good control of broadleaf weeds (McVicar et al. 2010).

2.4.2 Herbicide Use in Lentil

Lentil producers have a number of herbicide choices with respect to control of grassy weeds, however the same can not be said when it comes to controlling broadleaved weeds. Saskatchewan Agriculture thus recommends that producers select mostly weed-free fields for lentil production, and attempt to control difficult weeds in the years prior to lentil growth as there are limited registered broad leaf herbicide options for use in lentil (McVicar et al. 2010). The 2006 introduction of "Clearfield" lentils, which are tolerant to the Group 2 imadazolinone (IMI) herbicides imazamox and imazethapyr, represented a great advancement in broadleaf weed control in lentil. Since 2006 farmers have come to rely heavily on Group 2 herbicides to control broadleaved weeds in lentil (Beckie and Reboud 2009).

2.5 Group 2 Herbicides

Group 2 herbicides are a class of herbicides that inhibit acetolactate synthase (ALS), which may also be referred to as acetohydroxyacid synthase (AHAS). The ALS enzyme is the target site of the sulfonylurea (SU), imidazolinone (IMI), triazopyrimidine (TP), pyrimidinylthiobenzoate (PTB), and sulfonylaminocarbonyltriazolinone (SCT) herbicide chemical families. By inhibiting the ALS enzyme, these herbicides inhibit the biosynthesis of the branch-chain amino acids valine, leucine, and isoleucine (Whitcomb 1999). When sensitive species are treated with Group 2 herbicides symptoms including chlorosis, purpling, and necrosis of leaves, stunting, failure to produce viable reproductive structures, limited root growth, and plant death may occur. Since their commercialization in the early 1980s, Group 2 herbicides have been widely embraced due to their relatively low use rates, sound environmental properties, low mammalian toxicity, wide crop selectivity, and high efficacy (Devine and Shukla 2000, Saari et al. 1994). In addition, many Group 2 herbicides have residual activity, meaning they are able to persist in the environment and extend the period of weed control for some time after application (Whitcomb 1999).

2.6 Group 2 Herbicide Resistance

While group two herbicides are highly efficacious, they are also one of the most susceptible chemistries to development of herbicide resistant (HR) weeds, and there are now more species resistant to Group 2 herbicides than any other chemistry (Heap 2014a). The main mechanism for Group 2 herbicide resistance is target site mutation. Target site based resistance is due to point mutations within discrete conserved domains of the ALS gene (Devine and Eberlein 1997). This means that a change in one nucleotide in the DNA sequence of the gene results in an amino acid change in the protein target site; this changes the shape of the herbicide target site and results in the herbicide not being able to bind effectively. As of 2009, there were 22 identified nucleotide substitutions at seven sites across the ALS enzyme known to confer resistance to one of more families of ALS inhibitor herbicides (Powles and Yu 2010). Many of these mutations do not confer an evolutionary fitness penalty to the resistant individual, and thus the resistant populations can increase quickly (Tranel and Wright 2002). Although target site mutation is the most common resistance mechanism, metabolism-based resistance has also been identified in Group 2 resistant populations. This type of resistance occurs when an enzyme catalyzes enhanced rates of herbicide metabolism (Powles and Yu 2010). Metabolic resistance is not yet well understood in plants, but it is particularly troubling as it has been found to confer resistance to multiple herbicide modes of action, even those that have never been applied to the resistant population (Powles and Yu 2010).

The mechanisms conferring resistance help explain why Group 2 herbicide resistance can develop very quickly, and wide-spread resistance has been documented to develop in field populations in fewer than five applications of Group two products (Beckie 2006, Saari et al. 1994). In addition to the resistance mechanisms, characteristics of Group 2 herbicides and the manner in which producers apply them account for the high levels of resistance. The high levels of efficacy on a broad spectrum of weeds and the residual activity of Group 2 herbicides mean that they exert strong selection pressure for HR individuals. These characteristics also make them a desirable herbicide choice for producers. As a result Group 2 products are used repeatedly on a large number of acres each year. It was previously estimated that on the Canadian prairies Group 2 products are applied to approximately 30% of the total field crop acres annually (Beckie et al. 2007). More recent work by Beckie et al. (2013) indicates that Group 2 products continue to be used widely and repeatedly by producers. The continued repeated application of this chemistry further intensifies the selection pressure for Group 2 resistant weed species.

2.7 Group 2 Herbicide Resistant Wild Mustard in Lentil

Lack of herbicide options has lead to over-reliance on Group 2 herbicides in lentil and has selected for troublesome Group 2 resistant weed populations on prime lentil growing acres. A survey of herbicide use on the Canadian prairies indicated that Group 2 herbicides are applied on 48% of lentil acres (Beckie et al. 2013). One resistant weed of particular concern for prairie lentil producers is wild mustard (*Sinapis arvensis L.)*. Group 2 resistant wild mustard was first identified in Manitoba in 1992 (Morrisson and Devine 1994) and was subsequently identified in Saskatchewan in 2002 (Warwick et al. 2005). Characteristics inherent to wild mustard make it a troublesome herbicide resistant weed. It is a self-incompatible plant and is cross-pollinated by a number of insect pollinators (Mulligan and Bailey 1975). This trait combined with the fact that target site resistance to Group 2 herbicides can be spread by pollen, means that herbicide resistance can spread quickly through a population (Saari et al. 1994). Wild mustard also has long seed bank longevity; up to 60 years with little decrease in percent germination when seeds are buried in the ground for 10 years (Mulligan and Bailey 1975). Thus when herbicide resistant mustard seeds become part of the soil seed bank it becomes very difficult to eradicate the HR population.

Wild mustard is known to be a problematic weed in pulse crops as it has the potential to greatly reduce crop yields (McVicar et al. 2010). Twenty wild mustard plants m^{-2} have the ability to reduce pea (*Pisum sativum*) yield by up to 35 percent (Wall et al. 1991). A Manitoba study showed that 20 wild mustard plants m^{-2} was able to reduce navy bean (*Phaseolus vulgaris*) yield by up to 57 percent (Wall 1993). When Group 2 herbicides are no longer effective on wild mustard, lentil producers are currently left with few herbicides options and are in need of an alternative, reliable weed control strategy to maintain crop yields.

2.8 Non-Group 2 Herbicides for Lentil

At present only three non-Group two herbicides are registered in western Canada for in season control of broadleaf weeds in lentil. Two of these, trifluralin ({2,6-dinitro-N,N-dipropyl-4-(trifluoromethyl) benzenamine}; trade name: Treflan ™) and ethalfluralin ({N-ethyl-N-(2-methyl-2-propenyl)-2,6-dinitro-4-(trifluoromethyl) benzenamine}; trade name: Edge ™) are pre-emergent soil applied herbicides (SMA, 2013). Trifluralin and ethalfluralin are classified as group 3 herbicides and are active on both grassy and broadleaved weeds by affecting the roots and shoots of emerging weed seedlings. These herbicides have activity on a limited number of weed species and do not control cruciferous weeds such as wild mustard (Beckie et al. 2006, Wall and McMullan 1994). In addition efficacy of ethafluralin and trifluralin is influenced by soil and environmental conditions, and is often relatively low (Beckie et al. 2006). The only non-Group two post-emergent herbicide option registered for application in lentil is metribuzin (4-amino-6-tert-4,5-dihydro-3-methylthio-1,2,4-triazin-5-one; trade name Sencor ™) (SMA 2014). Metribuzin has been shown to cause significant injury in lentil crops. Leaf chlorosis, stand reduction, and decreased yields have been reported when metribuzin was applied at rates high enough to provide adequate weed control (Elkoca et al. 2004, Friesen and Wall 1986, Ghosheh and El-Shatnawi 2003). In addition research in pea and fababean (*Vicia faba*) has demonstrated that the injurious effects of metribuzin can also inhibit nodulation and nitrogenase activity in pulse crops (Bertholet and Clark 1985, Sprout et al. 1992). Saskatchewan Agriculture accordingly recommends that metribuzin should only be applied in lentil crops seeded more than 5 cm deep on soils with more than 4 percent organic matter, and only in the 1 to 4 node stage to avoid crop injury. It is recommended that full rate applications of metribuzin be split into two application timings in order to ensure crop safety (SMA 2014). A further complication is that metribuzin can not be tank mixed with graminicides, necessitating that graminicides must be applied in a separate application approximately five to seven days following application of metribuzin (SMA 2014). These additional investments of time and application costs are both expensive and inconvenient for producers and discourage the use of this herbicide.

2.9 Integrated Weed Management Systems

Integrated weed management systems have been successfully developed in several crops. In Australia an integrated weed management system has been developed to control herbicide resistant rigid ryegrass (*Lolium rigidum)* (Llewellyn and Lindner 2007). In Canada an integrated weed management system for barley (*Hordeum vulgare L.)* has been shown to allow wild oat (*Avena fatua)* herbicides to be applied at ¼ rates while maintaining acceptable weed control (Harker et al. 2009). A 23 site year study on the Canadian prairies showed that the practices of early seed date, increased crop seeding rate, fertilizer timing and reduction of recommended herbicide rate resulted in the most competitive cropping system. Not only did this more competitive integrated system provide weed control, it was also found that the weed seedbank was not greater than a system relying heavily on herbicides after four years of using 50% herbicide rates at two of the three locations (Blackshaw et al. 2005b).

Despite these examples of the successful development of IWM systems and the fact researchers have been championing their adoption for many years, producer uptake of IWM systems has been slow. Reliance on herbicides has continued to be the norm in western Canadian crop production. For an IWM system for lentils to be utilized by producers, the components should be shown to work well with herbicide application; the favoured weed control tactic of lentil growers.

2.10 Cultural Weed Control

Cultural practices in IWM attempt to shift the competitive balance and give crops an advantage to compete against weeds. The use of plant competition is regarded as one of the most inexpensive and most useful weed control practices available to all crop producers (Mohler 2001a). A simple but effective strategy to reduce weed competition is to increase the crop density by increasing the seeding rate. Mohler (2001) conducted an extensive review of 91 papers examining 29 crops and found only 6 cases where increasing crop density did not result in decreased weediness. By increasing seeding rate, the rate at which the crop occupies space early in the growing season and preempts weeds for resource acquisition is accelerated.

2.10.1 Increased Seeding Rates in Integrated Weed Management

Increasing crop-weed competition by increasing seeding rates has been shown to be an effective part of an integrated weed management system (Swanton and Weise 1991, Walsh and Powles 2007). Many studies have documented decreased weed biomass when crop density is increased (Ball et al. 1997, Townley-Smith and Wright 1994, Weiner 2001). Townley-Smith and Wright (1994) found that increasing seeding rate in field pea decreased both weed density and weed biomass. Ball et al. (1997) found that increasing lentil seeding rate contributed to weed suppression and also to the beneficial effects of herbicide use. The authors also noted that the benefits of increasing seeding rate were the most pronounced where herbicides were not applied or did not provide adequate weed control (Ball et al. 1997). This is parallel to the situation that would be faced by lentil producers who are unable to successfully use herbicides to control group two resistant weeds.

2.10.2 Interaction of Seeding Rate with Herbicide Rate in IWM

Lower herbicide rates have been documented to be much more likely to succeed in providing adequate weed control at lower weed densities (Blackshaw et al. 2006, Kirkland et al. 2000, O'Donovan and Newman 2004). Therefore integrating cultural practices that increase competition and decrease weed density, along with the use of herbicides at lower than recommended doses has been proposed as part of an integrated weed management strategy (Blackshaw et al. 2006). Increasing crop seeding rate has been found to be a simple and dependable method of enhancing crop competitive ability and improving the efficacy of herbicides applied at reduced doses (Blackshaw et al. 2005a).

Many studies have confirmed that reduced herbicide rates are more likely to be effective at greater than recommended seeding rates (Barton et al. 1992, Blackshaw et al. 2005b, O'Donovan and Newman 2004, Wille et al. 1998). O'Donovan and Newman (2004) documented markedly improved weed control with increased seeding rates in a canola-barley rotation when a reduced rate of herbicide was used. Blackshaw et al. (2005b) found that when seeding rate was increased by

150% decreasing herbicide rate did not result in increased weed biomass. Barton et al. (1992) found that increased seeding rate lowered wild oat biomass and also increased grain yield in barley, and that net return was the greatest in this system when wild oat herbicides were applied at half-rates. In a four-year study examining wild oat, Beckie and Kirkland (2003) concluded that by utilizing a combination of increased seeding rates and diverse crop rotations, herbicide rate could be reduced by up to 30%. This study also found that the rate of herbicide resistance from the weed seed bank and rate of weed seed bank return were slowed by using the integrated system, versus using the recommended seeding and herbicide rates (Beckie and Kirkland 2003). Not all studies have confirmed that increasing seeding rate allowed herbicide rate to be reduced. Kirkland et al. (2000) found that increasing seeding rate in several crops was not able to maintain crop productivity when herbicide rates were reduced.

2.10.3 Increased Seeding Rate for Lentil

Currently the recommended seeding rate for lentil in Western Canada is 130 plants m^{-2} (McVicar et al. 2010). This rate is lower than seeding rates used in other parts of the world. For example, in West Asia an optimal plant density of 275 – 300 plants m^{-2} is recommended (Silim et al. 1990) and an Italian study found optimal plant density to be 177-250 plants m^{-2} (Paolini et al. 2003). Recent work in organic lentil in Saskatchewan has shown that seeding rate should be increased (Baird et al. 2009). Baird et al. (2009) found that increasing seeding rate to 375 seeds m^{-2} provided maximum yield and weed suppression, as well as maximum economic return. Anderson et al. (2007) also suggest that increasing seeding rates is a feasible strategy for weed suppression in lentil; but conclude that due to lentils' low competitive ability, herbicides will still need to be utilized along with increased seeding rates. Despite this evidence to suggest increasing lentil seeding rate, Saskatchewan Agriculture and the Saskatchewan Pulse Growers both caution prairie producers against exceeding the recommended 130 plants m^{-2} due to increased risk of foliar diseases with a dense canopy (McVicar et al. 2010, SPG 2012).

2.11 Mechanical Weed Control

Mechanical weed control is agriculture's oldest form of weed removal (Mohler 1996). By physically removing weeds from the field the crop is given greater access to the space and resources required to grow and produce yield. Mechanical weed control has been shown to interact with chemical application to maximize weed control and crop yields (Burnside et al. 1994, Mohler 2001a, Mulder and Doll 1993, Snipes and Mueller 1992). Tillage is often criticized for having negative effects on soil tilth and causing erosion. However proper use of tillage can not only reduce weed populations it can also enhance water infiltration, facilitate fertility management, improve crop germination and establishment, and improve root growth (Mohler 1996). Furthermore it has been shown that systems that integrate reduced rate herbicide application with mechanical weed control often provide equivalent yield at lower costs than systems that rely exclusively on herbicides for weed control (Mohler 1996).

2.11.1 The Rotary Hoe for Weed Control in Lentil

Initial cohorts of annual weeds can be control non-chemically using shallow cultivation (Swanton and Weise 1991). The min-till rotary hoe is one implement that can be utilized for shallow tillage and shows potential for use in-crop in lentil. The rotary hoe has two sets of spiked wheels with spoon shaped tips attached at the end of its tips (Figure 2.1) (Shirtliffe and Johnson 2012). Optimum timing for rotary hoe operations has been found to be when soil conditions are relatively dry with a light crust and when weed seedlings are germinating but have not yet emerged (Lovely et al. 1958, Shirtliffe and Johnson 2012). Research in soybean (*Glycine max*) and navy bean has shown that timely rotary hoeing can decrease weed densities by 70-80% (Buhler et al. 1992, Lovely et al. 1958). In field pea rotary hoeing at three successive growth stages was able to reduce weed density by up to 75% (Shirtliffe and Johnson 2012). Studies also show that while crop density is often slightly reduced by multiple rotary hoe operations, yield is not typically affected (Buhler et al. 1992, Lovely et al. 1958). Rotary hoeing is most effective on small seeded weeds that emerge from shallow soil depths (less than 2.5 cm); wild mustard is one such weed that emerges from shallow soil depths (Endres et al. 1999). Recent research in field pea indicates that two passes with a rotary hoe, done at or just before the cotyledon stage of wild mustard provides maximum weed control (Shirtliffe and Johnson 2012).

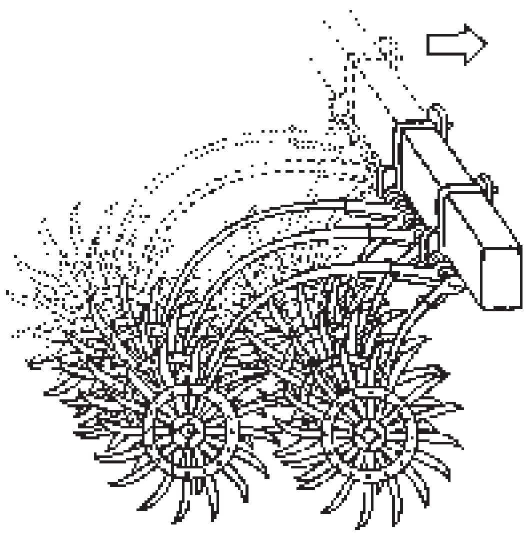

Figure 2.1 The rotary hoe removes shallow rooted weeds via the spinning wheels. Picture credit: Steel in the Field (Bowman 1997).

Lentil producers who have adopted minimum or zero-tillage will likely be concerned about how rotary hoes may fit into their system in terms of operating in and maintaining crop residues. The min-till rotary hoe is capable of operating in the presence of crop residues as extender arms for the implement can provide greater separation between the front and back wheels to avoid plugging with straw (Shirtliffe and Johnson, 2012). Research shows that hoeing with a min-till rotary hoe, up to 6 passes, does not result in a significant decrease in the surface residue and thus could be utilized in a conservation tillage production system (Shirtliffe and Johnson, 2012).

2.12 Use of Multiple Herbicide Mode of Actions

One of the most significant reasons cited for development of HR weed populations is the frequent use of the same herbicide mode of action (MOA). Rotation of herbicide MOA groups and the use of multiple MOAs sequentially or in mixtures during the growing season is a recommended practice to mitigate the risk of selection for herbicide resistant weeds (Matthews 1994). Herbicide rotation is defined as the application of herbicides with different sites of action to multiple crops over multiple growing seasons (Beckie et al. 2006). While herbicide rotation is a beneficial practice, the rapid rate at which ALS herbicides select for resistance means that this will only lead to a short-term delay in Group 2 resistance (Beckie and Reboud 2009). Beckie and Rebound (2009) suggest that a better strategy to delay Group 2 herbicide resistance is to use mixtures of Group 2 herbicides with suitable tank mix partners with different MOAs. However the lack of effective broadleaf herbicides registered in lentil makes both herbicide rotation and use of tank mixes difficult for lentil growers to implement. It is clear that the availability of additional MOAs for in-crop broadleaf weed control in lentil would be largely beneficial.

2.12.1 Group 14 Herbicides for Lentil

Research into new broadleaf herbicides for lentil has revealed some cross tolerance in current lentil genetics to both Group 2 and group 14 herbicides (Johnson 2012). These products could be applied either as tank mix partners with Group 2 products or sequentially with Group 2 products during the growing season. Tolerance to group 14 products in lentil would allow growers to utilize group 14 herbicides in imi-tolerant lentil to help mitigate and control Group 2 resistant weeds, such as wild mustard. Group 14 herbicides act on the pathway for chlorophyll and heme biosynthesis. They inhibit the enzyme protoporphyrinogen oxidase (PPO). When PPO is inhibited protoporphyrin accumulates in the plant cell and results in light dependent membrane damage (Matringe et al. 1989). Typically these herbicides are more active in dicots than in monocots. Characteristically PPO inhibitor herbicides have a rapid contact action, with symptoms including leaf burn, desiccation, and growth inhibition (Li and Nicholl 2005). PPO inhibitor herbicides have been utilized for approximately 40 years with just 6 reports of resistance occurring only in recent years (Heap 2014a). Commercialization of PPO inhibitor herbicides for in-crop application in lentil would give producers another herbicide tool to use in an integrated weed management system for control and prevention of Group 2 resistant weeds.

3 Integrated Weed Management System for Lentil

3.1 Introduction

Weeds are a major limiting factor in lentil production and have been noted to cause substantial yield loss (Boerboom and Young 1995, Swanton et al. 1993). Weeds compete against the crop for space, light, water, and nutrients. They can also harbor pests and diseases, and cause issues with mechanical harvesting (Brand et al. 2007). Lentils' low early season growth rate, short stature, slow canopy closure, and sparse canopy make them weakly competitive against weeds. Lentil has been ranked as the least competitive crop grown in western Canada (Swanton et al. 1993). Achieving good weed control is therefore essential for lentil growers.

Weed control in lentil has historically been challenging, as there are few registered herbicide options. Producers have a number of efficacious graminicides to use in lentil but few options exist for control of broadleaved weeds (Brand et al. 2007). Metribuzin is the only herbicide registered for post emergent control of broadleaved weeds. Metribuzin has been shown to cause injury to lentil crops including leaf chlorosis, stand reduction, and decreased yields (Friesen and Wall 1986, Ghosheh and El-Shatnawi 2003). Due to these crop safety concerns metribuzin has many application restrictions. It has a limited application window encompassing only the 1-4 node stage in lentil. Also, metribuzin can also not be tank mixed with graminicides, and graminicides must be applied five to seven days following metribuzin application (SMA 2014). The University of Saskatchewan Crop Development Center developed lentil varieties tolerant to the Group 2 imidazolinone herbicides in order to deal with the shortcomings in broadleaved weed control in lentil (Chant 2004). The introduction of these Group 2 tolerant varieties has provided growers with an efficacious herbicide choice for a broad range of grass and broadleaved weeds.

Group 2 herbicides are highly efficacious but are also one of the most susceptible chemistries to the development of herbicide resistant weeds. Group 2 resistance has been documented to have developed in fewer than five applications of Group 2 products (Beckie et al. 2006, Saari et al. 1994, Warwick et al. 2005). Group 2 products can be applied in a wide range of crops including Clearfield (CL) canola (*Brassica napus L.*) , CL wheat (*Triticum spp.)*, CL corn (*Zea mays)*, and field peas. It is estimated that annually approximately 30% of crop acres on the Canadian prairies receive an application of a Group 2 product (Beckie et al. 2007). The high level of efficacy and frequent use of Group 2 herbicides exerts strong selection pressure for herbicide resistant weed species.

Wild mustard (*Sinapis arvensis*) is one weed that has developed problematic Group 2 resistant populations on the Canadian prairies. Group 2 resistant wild mustard was first identified in Manitoba in 1992 (Morrisson and Devine 1994) and was subsequently identified in Saskatchewan in 2002 (Warwick et al. 2005). Resistance to Group 2 chemistries in Canadian wild mustard populations has been found to be due to both target site (Christoffers et al. 2010) as well as metabolic (Veldhuis et al. 2000) mechanisms. Wild mustard has been shown to be a problematic weed with the potential to greatly reduce yields in pulse crops (McVicar et al. 2010, Wall 1993, Wall et al. 1991). In addition, the efficacy of the only non-Group 2 in crop herbicide registered in lentil, metribuzin, has been shown to be variable on wild mustard (Cessna 1997). As a result, lentil producers can not rely on herbicides alone to achieve acceptable control of Group 2 herbicide resistant wild mustard.

Integrated weed management offers an alternative to a weed control strategy that relies solely on herbicides to control weeds and maintain crop yields. By integrating cultural and mechanical practices with herbicide application weed control and yield can be maintained while selection pressure for herbicide resistant weeds is reduced. Integrated systems have been found to be effective in a number of previous studies (Anderson 2005, Blackshaw et al. 2005a, Harker et al. 2003); however, no fully integrated system has been studied in lentil.

Group 2 resistant wild mustard in imi-tolerant lentil provides an ideal model system in which to study the effect of multiple tactic weed control. The objective of this study was to evaluate a system integrating cultural, mechanical, and chemical tactics to control wild mustard in lentil.

3.2 Materials and Methods

3.2.1 Site Description

Field experiments were conducted in 2011, 2012, and 2013 at Kernen Crop Research farm (KCRF)(52°16' N, 106°51' W) near Saskatoon, SK and at Agriculture and Agri-Food Canada Scott Research Farm (ACS) (52°36' N, 108°84' W). KCRF is located on a Sutherland series clay loam (Bradwell Dark Brown Chernozem; 10% sand, 40% silt, 50% clay), and ACS is on a loam soil (Dark Brown Chernozem; 38% sand, 40% silt, 21% clay).

3.2.2 Experimental Procedures

The experiment was a factorial design with three levels of seeding rate and six levels of weed control. The field layout was a randomized block design with four replicates.

The lentil variety seeded in each plot was CDC Impala, an extra small red imidazoline tolerant variety. Lentil seed was obtained from a local pedigreed seed grower. Lentils were seeded at KCRF using a cone seeder with disc openers on 20 cm row spacing. Tag Team® granular fungal and rhizobia inoculant (Novozymes, Saskatoon, Sk.) was applied with the seed at the recommended rate of 4.6 kg ha^{-1}.

Granular fertilizer was also applied mid-row in accordance with soil test recommendations. Immediately following lentil seeding, Xceed canola quality mustard (*Brassica juncea)* was seeded in the opposite direction of lentil seeding at a rate of 100 seeds m^{-2} as a proxy for wild mustard. *B. juncea* was used in this experiment to ensure even mustard populations among the plots. Plot size at KCRF was 4 m by 6 m. At ACS seeding was conducted using a cone seeder with disc openers on 25 cm row spacing. *B. Juncea* was broadcast perpendicular to the direction of crop seeding and the area was rotary hoed to incorporate the *B. juncea* seeds prior to lentil seeding in 2011 and 2012, and seeded perpendicular to the direction of lentil seeding in 2013. Tag Team® granular fungus and rhizobia inoculant (Novozymes, Saskatoon, Sk.) was applied with the seed at the recommended rate of 4.6 kg ha^{-1}. Granular fertilizer was applied seed placed according to soil test recommendations, however an equipment malfunction at ACS in 2012 caused the applied rate to be lower than the targeted fertilizer rate. Plot size at ACS was 4 m by 10 m. An application error in all the treatments containing saflufenacil occurred at ACS in 2013, resulting in these treatments receiving an increased rate of saflufenacil. As this error resulted in injury to the lentil crop and affected half of the plots at the site it was decided that this site should be removed from the analysis.

Prior to crop emergence, glyphosate was applied to the entire plot area at a rate of 450 g ai ha^{-1}. Saflufenacil (Heat ™) herbicide was applied at a rate of 18 g ai ha^{-1} prior to crop emergence in the applicable treatments. Metribuzin (Sencor ™) herbicide was applied at a rate of 102 g ai ha^{-1} for the half-rate treatments, or a rate of 206 g ai ha^{-1} for the full-rate treatments. The full-rate metribuzin treatment was split into two application timings as recommended for increased crop safety (SMA 2014). The half–rate application was applied on the same date as the first full-rate application, and approximately 7 days later the full-rate treatments received a second application. All herbicides were applied with a field scale tractor mounted sprayer equipped with Airmix™ 100015 nozzles calibrated to deliver a volume of

100 L ha^{-1} at 275 kPa for glyphosate and saflufenacil, and 175 L ha^{-1} at 275 kPa for metribuzin treatments. Plots were treated with pesticides to control non-target weeds, insects, and diseases (Table 3.1).

Table 3.1 Management of IWM Trial. NA – not applied.

	KCRF	ACS (2011)	KCRF	ACS (2012)	KCRF (2013)
Seeding Date	May 18	May 13	May 15	May 12	May 13
Glyphosate	May 20	May 14	May 18	May 11	May 14
Saflufenacil	May 20	May 14	May 18	May 11	May 14
Rotary Hoe	June 9	May 30, June 9	May 27, June 8	May 29, June 4	May 21
Crop and Weed Counts	May 30	May 30	May 30	May 31	May 27
Insecticide	NA	NA	June 2 (Deltamethrin)	NA	May 29 (Deltamethrin)
Sethoxydim	NA	NA	June 2, June 19	NA	June 26
Metribuzin (1st App)	June 8	June 1	June 1	June 1	May 28
Metribuzin (2nd App)	June 15	June 8	June 8	June 8	June 4
Imazamox	NA	NA	June 18	June 15	May 29, June 26
Fungicide	NA	July 28 (Pyraclostrobin + Boscalid)	June 29 (Boscalid), July 21 (Prothioconazole), Aug. 7 (Boscalid)	July 20 (Pyraclostrobin + Boscalid)	June 26 (Pyraclostrobin)
Biomass	Aug. 19	Aug. 5 & 8	Aug. 17	Aug. 23	Aug. 8
Desiccation (Diquat)	Aug. 30	Aug. 22	Aug. 21	Sept. 5	Aug. 20
Harvest	Sept. 6	Sept. 6	Aug.28	NA (Hail damage)	Aug 27

In-crop rotary hoeing was performed using two passes of a minimum-tillage rotary hoe (Yetter, Colchester, IL, USA). Rotary hoeing was performed at the optimum stage for weed control, when the *B. juncea* plants were at the white thread to early cotyledon stage. In some site-years, two rotary hoe operations were performed as a second cohort of mustard seedlings was observed emerging following the first rotary hoeing (Table 3.1).

Crop and weed population counts were taken prior to metribuzin application in two 0.25 m^2 quadrats per plot. Lentil and mustard as well as weeds were counted by species and recorded. Crop and weed biomass sampling was conducted at crop physiological maturity. Biomass samples were collected in two locations in each plot using 0.25 m^2 quadrats. The crop was separated from the weeds, and the *B. juncea* was separated from the other weed species. Samples were oven dried at 70°C for 48 hours and then weighed.

Disease severity ratings were calculated in 2012 and 2013 by estimating a percentage for the area of the plot exhibiting severe disease and for the area of the plot exhibiting little to no disease. Percentage of plant surfaces exhibiting disease symptoms within each of these two areas was then determined. For each area the percentage of plant surfaces exhibiting symptoms was multiplied by the portion of the plot occupied by that area. These two values were summed together to arrive at a final disease severity rating (Madden et al. 2007).

Lodging ratings were taken in 2012 and 2013. Lodging was calculated by measuring the height of the canopy near the front and back of the plot. The actual height of 3 plants located in different parts of the plot was also measured. The average height of the canopy and of the 3 measured plants was calculated. The canopy height was then divided by the plant height and multiplied by 100 to determine the percent lodging for each plot.

The plots were desiccated with diquat (6,7-Dihydrodipyrido[1,2-a:2',1'-c]pyrazinediium dibromide; Reglone ™) at 415 g ai ha^{-1} when the bottom third of the lentil pods had turned a tan colour and rattled when shaken (SPG 2012). Once dry down occurred, a strip in the middle section of plots was harvested with a plot harvester. At ACS in 2012 hail occurred following desiccation but prior to harvesting, and due to excessive shattering and resultant seed loss the plots were not harvested resulting in no yield data for this site-year. The harvested samples were air-dried and cleaned using a KornService™ machine (Continental Agra, Newston, KS, USA) prior to weighing.

Once cleaned yields were obtained an economic analysis was conducted to determine the potential economic benefit to producers of using the weed control strategies tested in this study. This analysis looked only at the difference between the gross profits from the yield of each treatment, minus only the costs associated directly with the weed control treatments tested. Assumptions made in this analysis were that red lentil seed cost $0.32 per pound, and had a selling price of $0.21 per pound. Cost of herbicide products was obtained from a Saskatoon area crop input retailer. Cost of applying the herbicides and rotary hoeing was calculated using the Saskatchewan Ministry of Agriculture Farm Machinery Custom Rate and Rental Guide (SMA 2013b).

1.1.1 Statistical Analysis

Statistical analyses were conducted using the MIXED procedure of SAS (SAS Institute Inc. 2011) for a two-way factorial RCB design. The effects of seeding rate and weed control treatment were treated as fixed effects. Seeding rate was analyzed as a categorical variable due to the inclusion of only three seeding rates in the study. The effects of site and rep nested in site were considered random factors. Yield data were analyzed with the 2011 and 2013 site years grouped and the 2012 site year analyzed separately. The 2012 data was analyzed separately due to a highly significant site-year by weed control treatment interaction ($P<0.001$). In this year the study experienced severe disease pressure and this caused the yield response to the treatments to be significantly different than in 2011 or 2013. A significant ($P<0.05$) site-year by weed control treatment interaction was still present in the combined 2011 and 2013 data, however analyzing the years separately revealed that the trends and the rankings of the treatments were the same, and only the magnitude of yield response appeared to differ between the years. Applying a general linear model to the data in SAS revealed that the site-year by weed control interaction only accounted for 5% of the type III sums of squares, therefore it was decided to analyze the 2011 and 2013 yield data together. Yield data were log

(log_{10}) transformed for the combined 2011 and KCRF 2013 data to satisfy the assumptions of ANOVA, back-transformed estimates and standard errors were presented for these data.

The mustard biomass data was analyzed with all site-years combined. The mustard biomass data required a square root transformation and was modeled with a repeated site-year statement to improve homogeneity of variance, and back-transformed estimates and standard errors are presented. A significant site-year by weed control treatment interaction was observed in the combined data. Separating the data by location removed this significant interaction, however the only difference in the interpretation of the results was a small increase in the saflufenacil efficacy at the ACS location versus the KCRF location. This was not surprising, as previous research has found saflufenacil to bind to heavier clay soils and be less available for uptake by plants (Gannon et al. 2014). The clay content at KCRF is approximately 50% versus 21% at ACS, thus saflufenacil would be expected to have greater efficacy at ACS. Furthermore this interaction accounted for just 10% of the type III sums of squares when the data were run in the GLM procedure of SAS. It was decided that the increase in interpretive value by combining the site years outweighed the importance of the relationship of saflufenacil efficacy to soil type, which has already been established in previous literature, and thus all site years of mustard biomass data are presented combined. Least squared means were used to determine treatment differences with significance declared at $p<0.05$.

3.3 Results and Discussion

3.3.1 Crop Emergence

Lentil density ranged from 61-65% of the targeted plant population, and was not significantly different among the treatments (data not shown). These emergence rates were similar to those previously reported in large green lentil grown under organic conditions by Baird et al. (2009).

3.3.2 Mustard Biomass

Mustard biomass was influenced by the interaction of seeding rate and weed control treatment (Figure 3.1). The full herbicide treatment provided the greatest and most consistent decrease in mustard biomass. This treatment did not respond to increasing seeding rate with decreased mustard biomass but rather had low mustard biomass at all three seeding rates. The remaining treatments show the same general trend of increased seeding rate resulting in decreased mustard biomass. The mechanical and integrated treatments demonstrate the most consistent trend in biomass decreasing with increasing seeding rate (Figure 3.1).

The lack of response to seeding rate by the full herbicide treatment was not unexpected based on previous findings. Increased seeding rates have previously been found to be more effective at reducing weed biomass in situations where herbicides are used at reduce rates or fail to provide acceptable efficacy (Ball et al. 1997, O'Donovan and Newman 2004). The efficacy of the full herbicide treatment in this study was high at all seeding rates, with reductions in weed biomass between 99-97% of the control treatment at the recommended seeding rate.

The response of the integrated weed control treatment to increased seeding rate is encouraging, and agrees with previous findings showing that integrating multiple weed control tactics can supplement herbicide application (Ball et al. 1997). The integrated treatment when compared to the 130 seeds m^{-2} control treatment achieved 68% reduction in mustard biomass at the recommended seeding rate. At the 520 seeds m^{-2} seeding rate an 89% reduction in mustard biomass was achieved. The downward trend in mustard biomass with increasing seeding rate seen in the integrated treatment shows that increasing seeding rate can interact with multiple tactic weed control to allow producers to achieve acceptable weed control.

The results presented in Figure 3.1 show that the optimum seeding rate for a producer depends on the selected weed control method. All of the weed control treatments, except the full herbicide treatment, benefited from increased crop competition provided by increasing crop density. This demonstrates that, even though lentil is widely regarded as a poorly competitive crop, increasing lentil density can provide weed management benefits when herbicides are not able to provide good weed control. These results agree with the previous findings of Ball et al. (1997), but refute those of Beckie and Kirkland (2003) who did not see a significant weed biomass reduction when lentil seeding rate was increased, even in the presence of uncontrolled weeds(Beckie and Kirkland 2003). Beckie and Kirkland (2003) only examined an increased seeding rate of 1.5X recommended; therefore, it is possible that had the researchers examined higher seeding rates they would have seen benefits of increasing crop density.

Source	Yield ¥	Yield §	Mustard Biomass
	kg ha^{-1}	kg ha^{-1}	g m^{-2}
Site-Year (SY)	NS	-	NS
Block(Site-Year)	*	-	NS
Seed Rate (SR)	*	NS	***
Weed Control Treatment (WC)	**	NS	***
SR*WC	***	NS	*
SY*SR	NS	-	NS
SY*WC	*	-	***
SY*SR*WC	NS	-	NS

*,**,***, significant at the 0.5, 0.01, and 0.001 probability levels respectively
¥ yield for 2011 and KCRF 2013 site years
§ yield for the 2012 KCRF site year

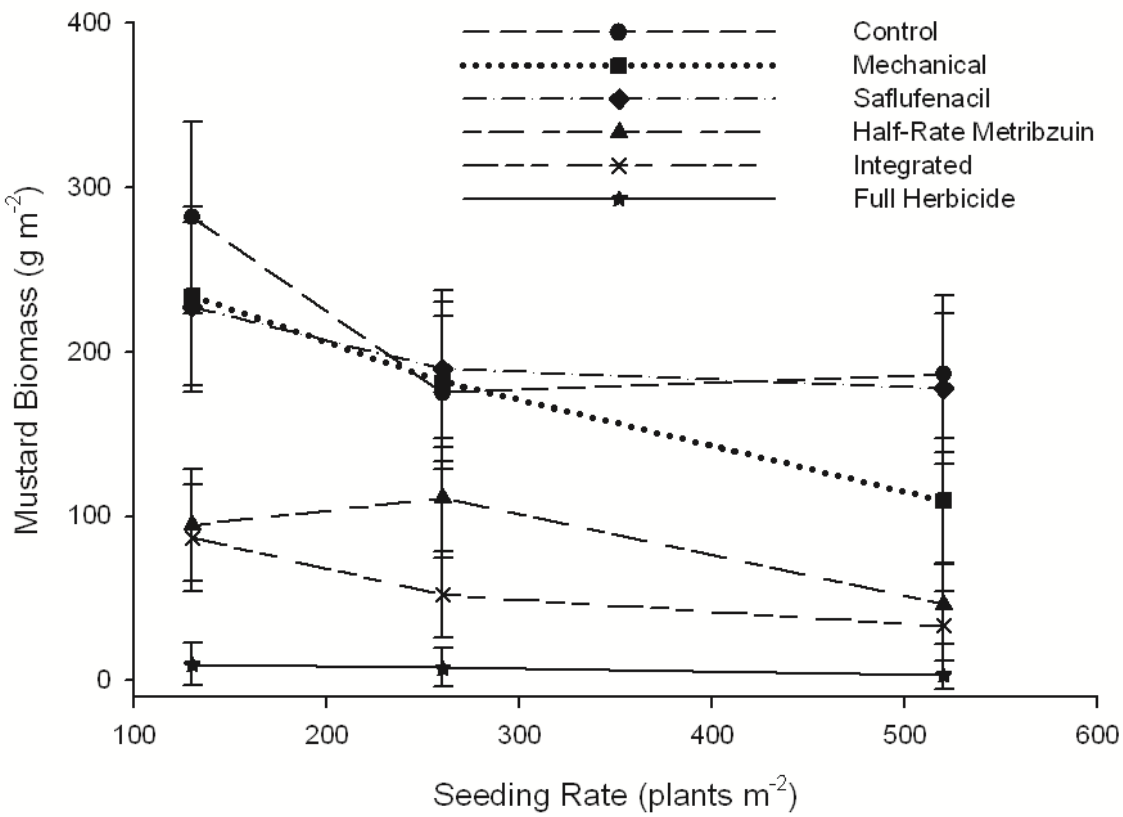

Figure 3.1 Interaction of seeding rate and weed control treatment on mustard biomass. Average of 5 site years (p<0.05).

3.3.3 Yield

The interaction of seeding rate and weed control treatment was significant in the 2011 and 2013 sites (Figure 3.2). At the recommended seeding rate the full herbicide treatment yielded significantly greater than any other treatment for the low disease sites (Fig 3.2). Furthermore, the full herbicide treatment had the lowest yield response to increased seeding rates. In contrast the lentil seed yield in the integrated treatment responded favorably to increased seeding rates. Although the integrated treatment yielded significantly lower than the full herbicide treatment at the recommended seeding rate, it yielded statistically equal to the full herbicide treatment when seeding rate was increased to 260 or 520 plants m^{-2}. Figure 3.2 shows that at the 520 plants m^{-2} the yield for the integrated treatment is maximized and almost identical to the full herbicide treatment. The remaining treatments also showed the same trend of increasing yield with increased seeding rate except for the saflufenacil treatment, which did not show a yield response.

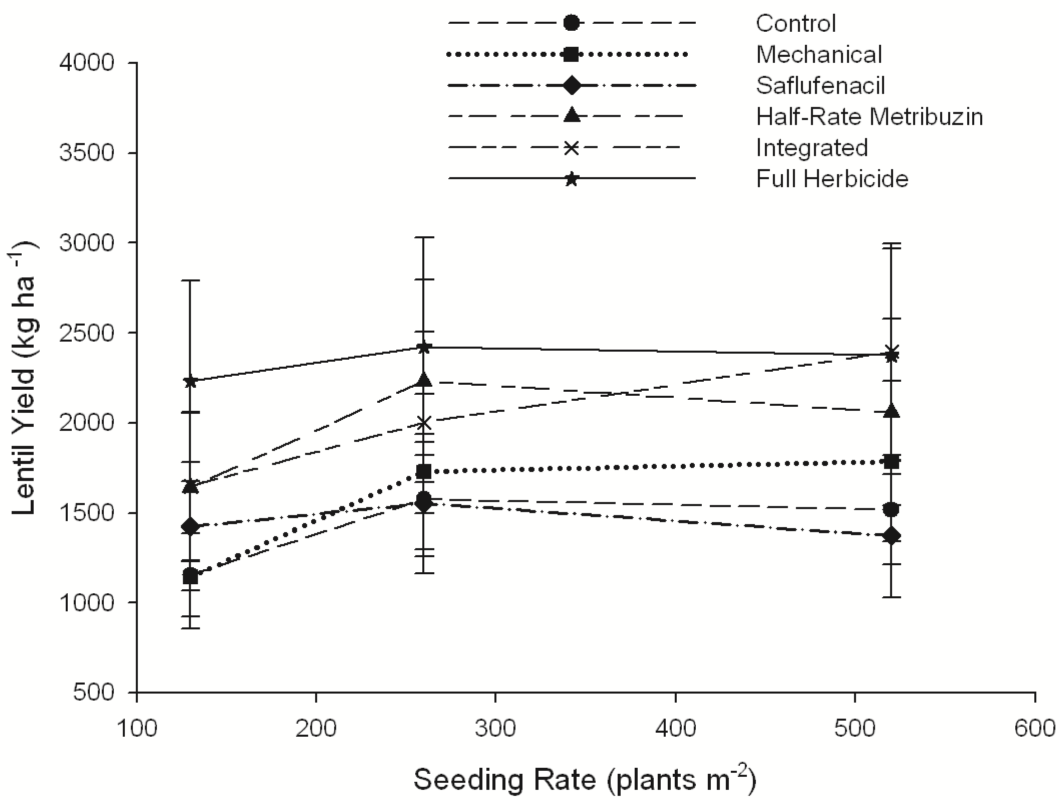

Figure 3.2 The effect of seeding rate and weed control strategy on lentil seed yield. Average of three site years. ($p<0.001$).

In 2012 neither seeding rate nor weed control treatment had an effect on lentil yield (data not shown). While this result may seem unimportant, some interesting environmental and agronomic observations were made during this year of study that could be quite pertinent with respect to the ability to increase seeding rate as part of an IWM strategy in lentil.

In 2012 the KCRF site experienced double the normal growing season precipitation (Table 3.1). Under these conditions the seeding rate and weed control treatments affected foliar disease, with higher seeding rates exhibiting a trend of having greater disease severity (Figure 3.3; $p=0.06$). Increasing crop density can impact foliar disease pressure due to creation of a denser canopy. Denser canopies result in increased lodging, reduced air movement, increased shading, and increased moisture retention in the canopy. These characteristics have been noted to increase severity of foliar diseases such as ascochyta blight, sclerotinia and botrytis stem rot (Davidson et al. 2004, Krupinsky et al. 2002, Taylor et al. 2007).

Table 3.1 - Weather data for IWM study

		Rainfall				Temperature			
Location	Month	2011	2012	2013	Normal ¥	2011	2012	2013	Normal ¥
		(mm)				(°C)			
KCRF	May	26	150	11	47	11.3	10.4	13.2	11.5
	June	119	113	121	61	15.9	16.2	15.9	16.0
	July	96	90	40	60	18.5	19.2	17.8	18.2
	August	40	66	14	39	17.0	18.3	18.7	17.3
	Total	281	419	186	207	-	-	-	-
ACS	May	31	51	-	36	10.1	9.7	-	10.9
	June	190	165	-	63	14.4	15.1	-	15.2
	July	76	56	-	71	17.0	18.6	-	17.0
	August	52	51	-	43	16.3	17.0	-	16.3
	Total	349	323	-	213	-	-	-	-

¥ 1970 – 2000 Canadian Climate normals obtained from Environment Canada (2013).

Weed control treatment significantly influenced disease severity in 2012 ($p<0.01$). Disease severity was significantly higher in the full herbicide and half metribuzin treatments than in the mechanical or integrated treatments (Figure 3.4). One explanation for these results is that the mechanical and integrated treatments are the two treatments where the rotary hoe was applied. It could be speculated that the action of the rotary hoe may have lead to some thinning of the lentil population and thus decreased disease pressure. In previous studies the rotary hoe has been noted to cause some stand reduction in lentils, though not enough to reduce yields (Shirtliffe and Johnson 2012). The full herbicide and half metribuzin treatments were also found to provide the greatest reduction in mustard biomass without the inclusion of rotary hoeing (Figure 3.1). Intercropping studies have shown that growing a vining legume crop along with a sturdy canola crop provides support for the legume and reduces lodging (Cowell et al. 1989, Waterer et al. 1994).

In the current study it was noted that mustard provided support for the lentils and that lodging was reduced in the plots containing more mustard (data not shown). This would help reduce yield losses due to disease. Although the weedier plots in the control, saflufenacil, and mechanical treatments may have suffered more due to competition, the deleterious effect of disease was simultaneously reduced due to reduced lodging. Thus yields were similar to plots that were more lodged but less influenced by weed competition. This helps to explain why the weed control treatments had no influence on yield in 2012.

Lentils are purported to be highly susceptible to lodging and disease, and it is often thought that increasing lentil seeding rate beyond the current recommendation will lead to severe lodging and disease infestation and consequently reduced yields (McVicar et al. 2010, SPG 2012). The 2012 KCRF site year experienced both lodging and severe disease infestation, and although increasing seeding rate did not result in increased yield in any weed control treatment it also did not lead to reduced yield. Although this is based on just one site-year of data, this result suggests that increased seeding rate may be, at worst, a yield neutral strategy in years with high disease pressure.

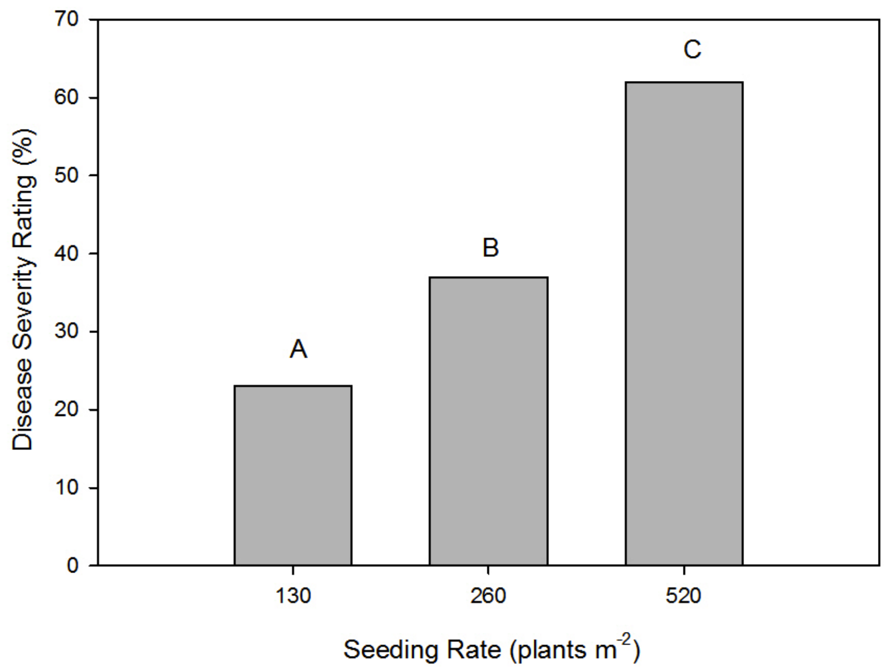

Figure 3.3 Increasing seeding rate increases foliar disease severity in 2012 (p<0.10).

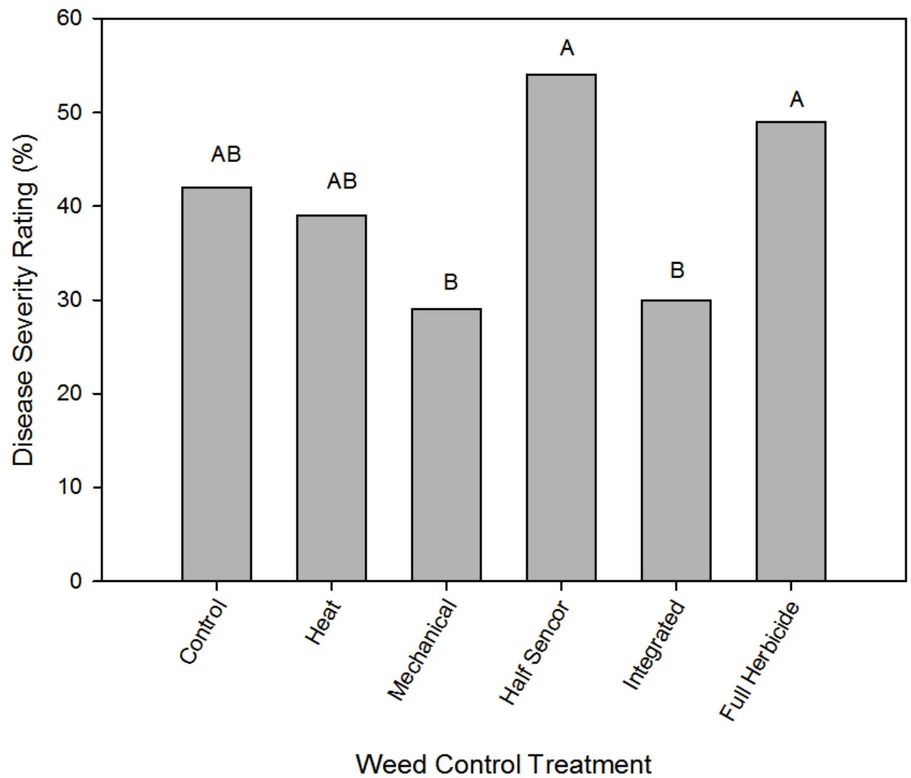

Figure 3.4 Mechanical and integrated weed control treatments had the lowest disease severity ratings, while full herbicide and half-rate metribuzin treatments had the highest ($p<0.01$).

3.3.4 Thousand Kernel Weight

Thousand kernel weights (TKW) were taken only for the 3 site-years at the KCRF location. Seeding rate did not affect TKW (data not shown). Increasing crop density has been suggested to reduce seed weight due to intraspecific competition (Salisbury 1942, Weiner 1988), but this deleterious effect was not observed in this study. Weed control treatment did influence TKW, with the three treatments that utilized metribuzin herbicide having on average 3-4% lower TKW than the control treatment. This is likely due to the injurious effects of metribuzin on the lentil crop (Elkoca et al. 2004, Friesen and Wall 1986, Ghosheh and El-Shatnawi 2003). Although the metribuzin did slightly reduce TKW, even at half-rate applications, this small reduction did not result in reduced yield compared to the other treatments.

3.3.5 Dockage

Dockage, in terms of mustard and other weed seeds, was taken in all three years of study at the KCRF location only. Both main effects of seeding rate and weed control treatment were found to significantly influence dockage ($p<0.01$). Increasing seeding rate beyond the recommended seeding rate decreased the percent dockage significantly (data not shown). Dockage was also found to be lowest in the full herbicide treatment though the integrated treatment was not significantly higher. The saflufenacil, and mechanical treatment did not result in reduced dockage compared to the control. The ability of the integrated treatment to reduce dockage to the same level as the full herbicide treatment is encouraging.

3.3.6 Economic Analysis

Results of the economic analysis for the four site years of study where yield data was collected are shown in Table 3.2. This analysis shows that in no site year did the glyphosate-only control treatment at the recommended seeding rate provide the best return. This indicates that producers with Group 2 herbicide resistant wild mustard populations will benefit financially by supplementing their weed control with additional tactics beyond a glyphosate burnoff and application of a Group 2 product. In the site years that experienced normal precipitation and disease pressure, increasing seeding rate improved returns for every weed control treatment. The integrated treatment achieved highest returns at the highest seeding rate, while the remaining five treatments maximized returns at the doubled seeding rate. The full herbicide treatment provided the greatest return of all 18 treatment combinations at the 260 plants m^{-2} rate. At the 520 plants m^{-2} rate the integrated treatment achieved returns very close to the full herbicide treatment at the 130 plants m^{-2} rate. Interestingly KCRF in 2012, which experienced excessive precipitation and disease pressure, saw optimum gains at the increased seeding rate of 260 plants m^{-2} with the mechanical treatment. It is unexpected that increasing seeding rate would still provide increased returns in a high disease year, yet this proved true for 4 of the 6 weed control treatments. These results indicate that producers should consider increasing seeding rate in extra small red lentils, not only for improved weed control but also for greater economic gains.

Table 3.2 Economic analysis of net profit for each treatment showed that increasing seeding rate to 260 plants m-2 resulted in increased profits in all treatments in years receiving normal precipitation (2011 & 2013).

Site-year(s)	Weed Control Treatment	Net Profit ($ ha^{-1}) Seeding Rate (plants m^{-2}) 130	260	520
2011 & 2013	Control	517.93	607.18	599.77
	Heat	637.19	667.55	518.10
	Hoe	518.43	768.25	740.09
	Half Sencor	771.11	1007.96	883.04
	Integrated	781.21	906.02	1011.66
	Full Herbicide	1032.43	1154.47	984.18
2012	Control	934.60	911.81	902.55
	Heat	893.21	844.41	927.82
	Hoe	951.77	980.28	750.74
	Half Sencor	846.11	926.01	774.71
	Integrated	849.26	930.55	747.77
	Full Herbicide	933.36	729.00	644.36

3.4 Conclusion

The utilization of a multi-tactic weed control strategy can result in yields equal to those realized in a system that relies entirely on herbicide application for weed control. In the three site years when yield was not influenced by excess moisture and disease pressure, the integrated treatment combined with increased seeding rate was able to produce yield equal to the full herbicide treatment.

The half-rate metribuzin treatment was also found to reduce mustard biomass and produce high yields when applied with increased seeding rate. The ability of the half-rate metribuzin treatment to yield equal to the full herbicide treatment when applied with a doubled seeding rate has practical implications for lentil growers. Metribuzin is a common lentil herbicide that is often not favoured by growers due to the risk of crop injury (Friesen and Wall 1986, SMA 2014). The cost of doubling the seeding rate, based on the TKW of CDC Improve and price of pedigreed seed at $0.32/lb, is similar to the cost of applying a full rate metribuzin treatment when the cost of a custom herbicide application is included. Thus by doubling their seeding rate producers could realize yield equal to that when the full rate of the herbicide is applied, without the risk of injuring their lentil crop. To achieve comparable weed biomass reduction of the full herbicide treatment however, producers would require the 4x seeding rate, which would represent a greater cost than applying a full rate of metribuzin herbicide.

These results may suggest that a fully integrated approach is not required and yields can be maximized with a single weed control tactic or by combining a single weed control tactic with the cultural practice of increasing seeding rate. This line of thinking would be short sighted however, as relying on a single tactic to produce yield relies too heavily on that weed control tactic and yield may be severely compromised if that tactic fails. Furthermore, relying solely on herbicides to control herbicide resistant weed populations only serves to create a population resistant to multiple herbicide chemistries in the longer term. The results of this study also show that increasing seeding rate in extra small red lentils reliably increases lentil yield in more typical growing seasons and is yield neutral in very wet years. Increasing seeding rate was also found to have generally positive economic results regardless of the weed control strategy selected by the grower. This suggests that seeding rate recommendations in the extra small lentil seed size class should be re-examined.

3.5 Prologue to Chapter 4

The results of chapter 3 show that utilization of an integrated weed control system can result in yield, weed biomass reduction, and profit comparable to that of a system that relies strictly on herbicides. Increasing crop competitive ability by increasing seeding rate beyond the recommended 130 plants m^{-2} rate was found to result in greater yield and weed biomass reduction when combined with the mechanical and chemical tactics applied in the weed control treatments. This shows that there is an important relationship between seeding rate and chemical weed control. However the results are specific to the weed control tactics and 3 seeding rate treatments applied in this study and thus do not describe the overall relationship. A study was therefore conducted to more thoroughly examine the seeding rate, herbicide rate relationship using dose response analysis. This study is presented in manuscript form in chapter 4.

4 Seeding Rate Influence on Dose Response of Mustard to Fluthiacet-Methyl

4.1 Introduction

A major challenge facing prairie lentil growers is achieving good weed control in lentil. Lentils' short stature, slow canopy closure, and relatively slow development rate make it a poor competitor against weeds (Kirkland et al. 2000). In particular, farmers have traditionally struggled with achieving good control of broadleaf weeds in lentil (McVicar et al. 2010). The 2007 introduction of Clearfield™ lentils, which are tolerant to the Group 2 IMI herbicides imazamox and imazethapyr, resulted in more effective broadleaf weed control. Since 2007 farmers have come to rely heavily on Group 2 herbicides to control broadleaf weeds in lentil (Beckie and Reboud 2009). While Group 2 herbicides are highly efficacious, they are also one of the most susceptible chemistries to development of herbicide resistant weeds; currently there are 23 known weed species with Group 2 resistant biotypes in Canada (Heap 2014a). Group 2 resistance can develop very quickly and was documented to form in field populations in fewer than five applications of Group 2 products (Beckie 2006). Thus, it is not surprising that Group 2 resistant broadleaf weeds have evolved and are presenting a serious weed control issue for prairie lentil producers. One weed that is of particular concern to lentil growers when resistant to Group 2 herbicides is wild mustard (*Sinapis arvensis L.).* In Canada, Group 2 resistant wild mustard was first identified in Manitoba in 1992 (Morrsion and Devine 1994) and was identified in Saskatchewan in 2002 (Warwick et al. 2005). Wild mustard is a problematic weed in pulse crops as it is difficult to control and has potential to induce significant yield loss (McVicar et al. 2010). Lack of in-crop herbicide options to control wild mustard in lentil has highlighted a need for research into both new herbicide chemistries for use in lentil, as well as development of an integrated weed management strategy that combines these herbicides with cultural practices to increase weed control and decrease selection pressure for further development of herbicide resistant weeds.

Increasing crop-weed competition by increasing seeding rates has been shown to be an effective part of an integrated weed management system (Swanton and Weise 1991, Walsh and Powles 2007). Currently the recommended seeding rate for lentil in Western Canada is 130 plants m^{-2} (McVicar et al. 2010). This rate is lower than seeding rates used in other parts of the world. For example in West Asia the optimal plant density was 275 – 300 plants m^{-2} (Silim et al. 1990) and in an Italian study it was 177 - 250 plants m^{-2} (Paolini et al. 2003). Recent work in organic lentil in Saskatchewan has shown that seeding rate should be greater than the recommended rate for conventionally grown lentils, and found that increasing seeding rate to 375 seeds m^{-2} provided maximum yield and weed suppression, as well as maximum economic return (Baird et al. 2009).

Integrating cultural practices that increase crop competition and decrease weed density, along with the use of herbicides at lower doses has been proposed as part of an integrated weed management strategy (Blackshaw et al. 2006). Increasing crop seeding rate has been found to be a simple and dependable method of enhancing crop competitive ability and improving the efficacy of herbicides applied at lower doses (Blackshaw et al. 2006). Many studies have confirmed that lower herbicide rates are more likely to be effective at greater than recommended seeding rates (Barton et al. 1992, Blackshaw et al. 2005a, 2006, 2002, O'Donovan and Newman 2004). These studies provide a useful knowledge base regarding the interaction of increased seeding rates with herbicide application; however, the vast majority of these studies have looked at the relationship empirically, using means separation to compare the specific treatments examined in the studies . One exception is a study examining the seeding rate and herbicide rate relationship on weed control in a canola-barley rotation, which utilized non-linear regression and dose response analysis (O'Donovan and Newman 2004). O'Donovan and Newman (2004) documented markedly improved weed control with increased seeding rates in a canola-barley rotation when reduced herbicide rates were applied. The O'Donovan and Newman (2004) study demonstrated how dose response analysis can be used to examine the seeding rate-herbicide rate relationship. The following study aimed to expand on O'Donovan and Newman's findings and more precisely describe how seeding rate influences the parameters of the dose response curve.

The objective of this experiment was to determine how plant population influences herbicide efficacy. Dose response analysis was used to explore this relationship as it is an important tool in weed science, and typically aids in the understanding of herbicide efficacy and mode of action (Seefeldt et al. 1995). By increasing crop seeding rate and altering the competitive balance with weeds, it is believed that the parameters of the dose response curve will shift and herbicide efficacy will increase. Practically this shift in the dose response curve would mean that producers could achieve acceptable weed control when applying less efficacious herbicides and in conditions when herbicides fail to achieve good efficacy due to environmental conditions.

4.2 Materials and Methods

4.2.1 Site Description and Experimental Design

Field experiments were conducted at two locations near Saskatoon, SK. in 2012 and 2013. Sites were located at the Kernen Crop Research Farm (KCRF) (52°16' N, 106°51' W; Sutherland Orthic Dark Brown Loam; 10% Sand, 40% Silt, 50% Clay) and Skarsgard Research Farm (SKARS) (52°05' N, 106°43' W; Elstow Orthic Dark Brown Loam; 28% Sand, 55% Silt, 17% Clay) in 2012, and in 2013 sites were located at KCRF and Goodale Crop Research Farm (GOOD) (52°06' N, 106°49' W; Bradwell Fine Sandy Loam; 42% Sand, 41% Silt, 17% Clay).

The experimental design was a 2 way factorial randomized complete block design with 4 replicates. One factor was seeding rate with 4 levels (70, 140, 280, and 560 plants m^{-2}). The current recommended lentil seeding rate in western Canada is approximately 140 plants m^{-2}. The second factor was rate of fluthiacet-methyl (acetic acid[[2-chloro-4-fluoro-5- [(tetrahydro-3-oxo-1H,3H- [1,3,4]thiadiazolo[3,4-_]pyridazin-1- ylidene)amino]phenyl]thio]-methyl ester; Trade name: Cadet ™)) herbicide with 7 levels of herbicide rate. Fluthiacet-methyl herbicide was chosen, as it is showing potential for in-crop registration in lentil (C. Willenborg, Pers. Comm.). A plot size of 2.25 X 6m was utilized at all sites.

4.2.2 Experimental Procedures

The lentil variety CDC Improve was obtained from a local pedigreed seed grower and seeded in each plot. CDC Improve is a large green imidazoline tolerant variety, identified in previous University of Saskatchewan research to have the greatest tolerance to fluthiacet-methyl among current germplasm (C. Willenborg, Pers. Comm.). Lentils were seeded using a cone seeder with disc openers on 20 cm row spacing at a depth of approximately 4 cm. Tag Team® fungal and rhizobia granular inoculant was applied with the seed at the recommended rate of 4.6 kg ha^{-1} (Novozymes, Saskatoon, Sk.). Granular 11-52-0 fertilizer was applied mid-row in accordance with soil test recommendations. Immediately following lentil seeding, Xceed canola quality mustard (*Brassica juncea*) was seeded perpendicular to the direction of lentil at a rate of 100 seeds m^{-2} as a proxy for wild mustard. Seeding rates for both the lentils and the *B. juncea* were adjusted for thousand kernel weights and percent germination. Prior to seeding all plots were treated with glyphosate at a rate of 450 g ai ha^{-1}. Non-target weeds, insects, and diseases were controlled using pesticides at recommended label rates (Table 4.1).

Table 4.1 Field operations for the dose response study.

	KCRF (2012)	SKARS (2012)	KCRF (2013)	GOOD (2013)
Seeding Date	May 15	June 1	May 13	May 24
Insecticide (Deltamethrin)	June 2	NA	May 29	NA
Crop and Weed Counts	June 8	June 22	May 28	June 3
Imazamox	June 2	June 13	May 29, June 26	June 12, June 28
Fluthiacet-Methyl treatment sprays	June 21	June 22	June 5	June 26
Graminicide	June 26 Clethodim	June 26 Clethodim	May 29 Sethoxydim	June 12 Sethoxydim
Biomass (21 Days After Treatment Spraying)	July 12	July 13	June 27	July 17
Fungicide	July 6 Prothioconazole July 21 Prothioconazole Aug.7 Boscalid	July 6 Prothioconazole July 21 Prothioconazole Aug. 7 Boscalid	June 26 Pyraclostrobin	June 28 Pyraclostrobin
Biomass (physiological maturity)	Aug. 17 & Aug. 20	Aug. 22	Aug. 8	Aug. 12
Desiccation (Diquat)	Aug. 30	Sept.5	Aug. 23	Aug. 26
Harvest	Sept. 10	Sept. 17	Aug. 27	Sept. 7

Fluthiacet methyl was applied at rates of 0, 0.94, 1.87, 3.75, 7.5, 15, and 30 g ai ha^{-1} with Agral-90 surfactant at 0.5% v/v, when *B. Juncea* reached the 2-3 leaf stage SKARS and NAS in 2012 and 2013, respectively. However, at KCRF and GOOD in 2012 and 2013, rain caused application to be delayed to the 5-6 leaf stage of the *B. Juncea*. Applications of fluthiacet methyl were made with a tractor mounted sprayer equipped with Airmix™ 100015 nozzles calibrated to deliver a volume of 150 L ha^{-1} at 275 kPa.

Crop and weed density counts were taken at the 4-node stage of the crop. Two 0.25 m^2 quadrats were counted per plot. Lentil plants were counted and recorded; mustard and other weedy plants were identified by species and enumerated. Crop and weed biomass sampling was conducted at 21 days after fluthiacet-methyl application and again at crop physiological maturity in two, 0.25 m^2 quadrants. The crop was separated from the weeds, and the mustard was subsequently separated from the other weed species. Samples were oven dried at 70°C for 48 hours and then weighed.

Disease severity ratings were calculated by estimating a percentage for the area of the plot exhibiting severe disease and for the area of the plot exhibiting little to no disease. Percentage of plant surfaces exhibiting disease symptoms within each of these two areas was then determined. For each area the percentage of plant surfaces exhibiting symptoms was multiplied by the portion of the plot occupied by that area. These two values were summed together to arrive at a final disease severity rating (Madden et al. 2007).

Lodging ratings were taken near physiological maturity, prior to desiccation. Lodging was calculated by measuring the height of the lentil canopy in 2 locations in the plot. The actual height of 3 plants located in different parts of the plot was also measured. The average height of the canopy and of the 3 measured plants was calculated. The averaged crop height was then divided by the averaged canopy height and multiplied by 100 to determine the percent lodging for each plot.
The plots were desiccated with diquat (6,7-Dihydrodipyrido[1,2-a:2',1'-c]pyrazinediium dibromide; Reglone ™) at a rate of 415 g ai ha^{-1} when the bottom third of the lentil pods had turned a tan colour and rattled when shaken (SPG 2012). Once dry down occurred, the middle 1.8 m section of the plots was harvested with a plot harvester. The harvested samples were cleaned using a KornService™ machine and dockage was recorded. The samples were then weighed to determine clean yield and thousand kernel weights were taken.

An economic analysis was performed to determine differences between treatments in net profits. Revenue for seed yield for each treatment was discounted by the costs associated directly with the weed control treatments. Assumptions made in this analysis (based on data available at the time of analysis) were that pedigreed large green lentil seed cost $0.38 per pound, and the crop had a selling price of $0.22 per pound. The cost of the Cadet herbicide was difficult to discern, as it is not currently available to purchase in western Canada. A cost of $315 per liter was assumed based on what comparable herbicides currently sell for locally and the value of the herbicide in the USA (information from online farm message boards). Cost of herbicide application was based on the Saskatchewan Ministry of Agriculture Farm Machinery Custom Rate and Rental Guide (SMA 2013b).

4.2.3 Statistical Analysis

Statistical analysis was conducted using the DRC package (Ritz and Streibig 2005) of R (R Core Team 2013) and the MIXED procedure in SAS (SAS Institute Inc. 2011). The MIXED procedure was used to conduct variance components analysis and remove the variation for site and rep. These adjusted data were then utilized to construct non-linear models using the DRC package in R. Data were analyzed separately for each year due to highly significant treatment by year interactions. When data was examined for individual years there were no site by treatment interactions and all models converged in DRC with highly insignificant lack of fit tests.

The 3 parameter log logistic model was utilized to model early mustard biomass in both years and late mustard biomass in 2012 (Equation 4.1). However the 4 parameter log logistic model better fit the late mustard biomass data collected at maturity in 2013 (Equation 4.2).

In the 4 parameter model, Y represents mustard biomass, *d* and *c* parameters represent the upper and lower horizontal asymptotes, respectively, the *e* parameter is commonly referred to as the ED_{50} and describes the dose required to reduce biomass by 50%, while the *b* parameter describes the slope around the ED_{50}. The 3 parameter model is a simplification of the 4 parameter model where the *c* parameter is fixed at 0. In both 2012 models and in 2013 maturity model strong heterogeneity of variance was noted and the optimal Box-Cox transformation was applied to correct for heterogeneity and ensure true standard errors were reported (Box and Cox 1964).

$$Y = \frac{d}{(1+\exp\{b(\log(x)-\log(e))\}}$$ **Equation 4.1 3-Parameter log-logistic equation for mustard biomass**

$$\boldsymbol{Y = c + \frac{d-c}{(1+\exp\{b(\log(x)-\log(e))\}]}}$$ **Equation 4.2 4-Parameter log-logistic equation for mustard biomass**

The 4 parameter Brain Cousens hormesis model was utilized to model yield data (Equation 4.3)(Brain and Cousens 1989). Hormesis occured where low doses of herbicide caused a stimulation in lentil yield. In this equation both the b and e parameters lack a direct biological interpretation. The d parameter represents the upper aymptote . The f parameter indicates the size of the hormesis response.

Model selection for all models was based on criteria of least significant lack of fit test, and examination of model fit to the data and of the model residuals. In some cases no differences existed between parameter estimates among the four seeding rates. When this occurred a common parameter was fit when doing so resulted in an improved model lack of fit test statistic.

$$\boldsymbol{Y = \frac{d+f\mathrm{x}}{1+\exp\{\mathrm{b}(\log(x)-\log(e)\}}}$$ **Equation 4.3 Brain Cousens hormesis equation for lentil yield**

Measurements of crop emergence, crop biomass, disease severity ratings, and lodging were examined using mixed model analysis in SAS. The effects of seeding rate and herbicide rate were treated as fixed effects. The effects of site and rep nested in site were considered random factors. Least squared means were used to determine treatment differences with significance declared at $p<0.05$.

4.3 Results & Discussion

4.3.1 Lentil Emergence

Emergence rates ranged from 69 – 79% and thus, actual crop densities were lower than the targeted plant population at all seeding rates. There was no statistical difference in percent emergence between any of the seeding rates (data not shown). These emergence rates were slightly higher than those previously reported in large green lentil grown under organic conditions by Baird et al. (2009).

4.3.2 Mustard Biomass

Increasing seeding rate resulted in a reduction in mustard biomass when herbicides were not applied or were applied at low rates (Figure 4.1). In each year of the study at both the early and late biomass timings, increasing seeding rate resulted in a near linear relationship between increased seeding rate and the value of the *d* parameter which indicates that less mustard biomass was present in the untreated plots (Figure 4.2).

In 2012 increasing seeding rate lowered ED_{50} value at both early and late biomass timings (Table 4.2). At the early biomass timing a relatively constant reduction in ED_{50} was observed as seeding rate increased (Figure 4.3). At the late biomass timing there was a large difference between the ED_{50} values of the lowest two seeding rates and the highest two seeding rates (Figure 4.3). ED_{50} was 3.6 g ai ha^{-1} lower for the 280 plants m^{-2} rate than for the 140 plants m^{-2} rate (Table 4.2).

In 2013 ED_{50} was not affected by increasing seeding rate and a common ED_{50} parameter was fit to all four seeding rate curves. This ED_{50} estimate is much lower than the 2012 estimates for the lower two seeding rates. The ability of seeding rate to cause such a significant reduction in the *d* parameter (mustard biomass of the unsprayed check plots) meant that although ED_{50} was not reduced by increasing seeding rate in 2013, there was still less actual mustard biomass in the plots at a given seeding rate within the range of reasonable application rates (up to the 7.5 g ai ha^{-1} rate).

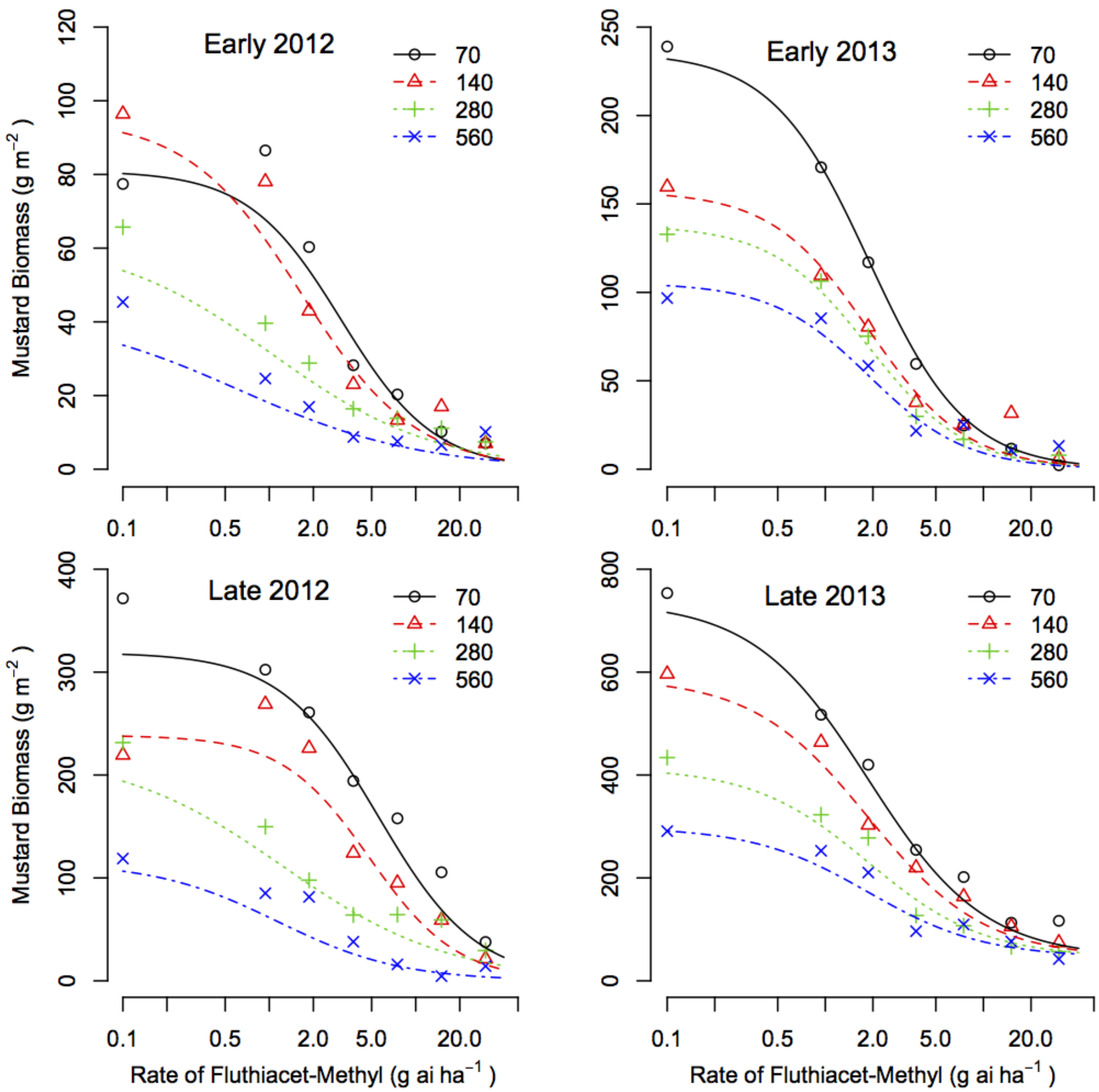

Figure 4.1Dose response curves for early and late mustard biomass in 2012 and 2013 show that increasing seeding rate reduced mustard biomass and shifted curve downward. Curves indicate seeding rates (plants m^{-2}).

Table 4.2 Model parameter estimates for early and late mustard biomass with standard errors in brackets. Lack of fit test statistics for early 2012 and 2013 models and late 2012 and 2013 models are 0.8374, 0.9998, 0.9515, and 0.9728 respectively.

Parameter	Seeding Rate (plants m^{-2})	Early 2012	Early 2013	Late 2012	Late 2013
D (Upper Limit)	70	80.9 (10.0)	235.6 (13.2)	319.0 (56.1)	736.5 (54.5)
	140	95.3 (11.9)	157.2 (12.1)	238.5 (36.9)	588.6 (46.8)
	280	62.5 (10.2)	138.0 (11.7)	222.2 (45.7)	414.5 (37.6)
	560	42.9 (8.4)	105.4 (11.4)	115.2 (26.6)	298.7 (31.9)
E (ED50)	70	3.10 (0.83)	1.89 (0.21)	5.57 (2.53)	1.87 (0.29)
	140	1.66 (0.49)	1.89 (0.21)	4.85 (1.58)	1.87 (0.29)
	280	1.04 (0.59)	1.89 (0.21)	1.25 (0.80)	1.87 (0.29)
	560	0.63 (0.53)	1.89 (0.21)	1.14 (0.61)	1.87 (0.29)
B (Slope)	70	1.4 (0.24)	1.4 (0.19)	1.3 (0.37)	1.2 (0.20)
	140	1.1 (0.19)	1.4 (0.19)	1.5 (0.29)	1.2 (0.20)
	280	0.8 (0.19)	1.4 (0.19)	0.8 (0.17)	1.2 (0.20)
	560	0.7 (0.25)	1.4 (0.19)	1.0 (0.22)	1.2 (0.20)
C (Lower Limit)	Common	NA	NA	NA	45.5 (17.2)

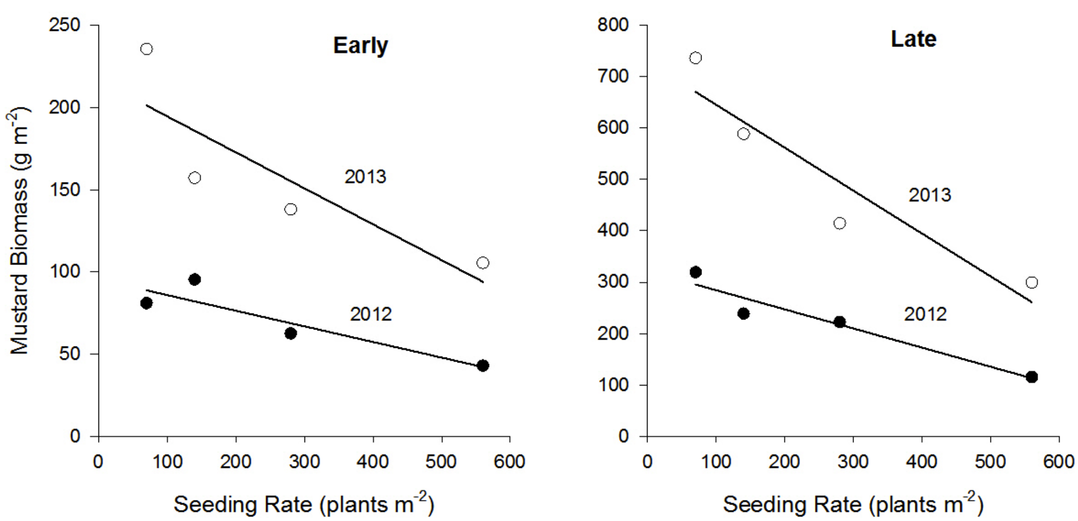

Figure 4.2 Increasing seeding rate consistently reduced the d parameter at both early and late biomass sampling in 2012 and 2013. P values for the early timing in 2012 and 2013 are 0.09 and 0.14 respectively. P values for the late timing in 2012 and 2013 are 0.03 and 0.05 respectively.

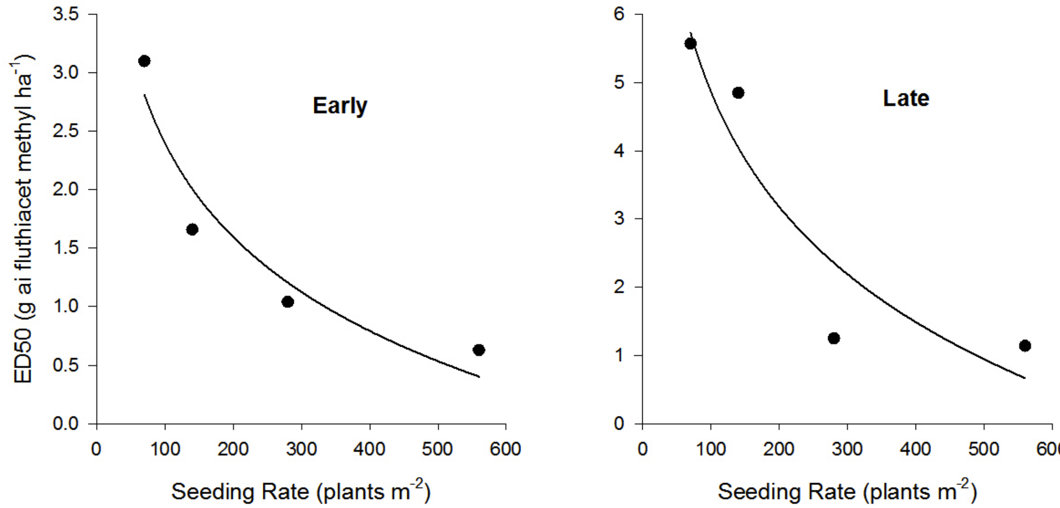

Figure 4.3 ED50 was reduced with increasing seeding rate in 2012 at early and late mustard biomass sampling. P values for 2012 early and late samplings were 0.0413 and 0.0670 respectively, R squared values are 0.9191 and 0.8705 respectively.

Table 4.3 Weather data for the study period obtained from Environment Canada.

Month	Rainfall			Temperature		
	2012	2013	Normal ¥	2012	2013	Normal ¥
	(mm)			(°C)		
May	143	11	47	9.8	13.2	11.5
June	97	121	61	15.6	15.9	16.0
July	83	40	60	19.6	17.8	18.2
August	66	14	39	17.8	18.7	17.3
Total	389	186	207	-	-	-

¥ 1970 – 2000 Canadian Climate normals obtained from Environment Canada (2013).

The mustard biomass measurements in the study indicate that increasing seeding rate results in the alteration of the dose response curve. In both years the d parameter was reduced as the competitive effect of increased crop density resulted in lower mustard biomass in the unsprayed plots. Increasing seeding rate resulted in lower weed biomass at all but the highest herbicide rates in both years. This agrees with previous findings in other crops (O'Donovan and Newman 2004, O'Donovan et al. 2001). In 2012 the ED_{50} parameter was lowered at increased seeding rates. The 3.6 g ai ha^{-1} reduction in ED_{50} observed in the late biomass in 2012 by doubling the seeding rate from 140 to 280 plants m^{-2} is also of great practical significance when one considers that the recommended rate for this herbicide in lentil will likely be approximately 4 g ai ha^{-1} (Ken Sapsford, Pers. Comm.). This large decrease in ED_{50} indicates that increasing seeding rate can be a useful tactic to ensure adequate herbicide efficacy is achieved when herbicides do not perform as expected in field situations.

4.3.3 Thousand Kernel Weights

In 2012 neither seeding rate nor herbicide rate had a significant effect on lentil thousand kernel weight (TKW). In 2013 only herbicide rate significantly influenced TKW ($p<0.01$). In 2013 herbicide rates higher than 7.5 g ai ha^{-1} caused significant reduction of TKW compared to the unsprayed check (data not shown). The fact that herbicide rate did not influence TKW in 2012 but did in 2013 suggests that the herbicide had a greater phytotoxic effect in 2013.

4.3.4 Yield

In general lentil seed yield increased at all seeding rates as herbicide rate was increased up to the herbicide rate of 7.5 g ai ha^{-1}, as the herbicide provided mustard control and gave the lentils a competitive advantage. Seed yield then generally decreased as herbicide rates above 7.5 g ai ha^{-1} had phytotoxic effects on the lentil plants and inhibited growth and yield formation (Figure 4.5). In both years the 70 and 560 plants m^{-2} rates appeared to be too low and high respectively to be expected to achieve optimum yield at any herbicide rate. Greatest yields in this study were generally obtained at seeding rates of 140 and 280 plants m^{-2} (Figure 4.5)

In 2012 the 140 and 280 seeding rates achieved similar yields when herbicide was applied at rates of 3.75 or 7.5 g ai ha^{-1}, but the 140 plants m^{-2} seeding rate was much more reliant on herbicide application to achieve higher yield, compared to the 280 plants m^{-2} seeding rate. In 2013, the greater reliance on herbicide application to achieve maximum yield observed in the 140 plants m^{-2} rate versus the 280 plants m^{-2} seeding rate observed in 2012 was not seen, and yield remained relatively stable at both seeding rates.

It is interesting and perhaps unexpected that the 560 plants m^{-2} curve experienced a yield decline all along the curve as herbicide rate was increased in 2012, and maximum yield on this curve was achieved with no herbicide application. This was the only curve to deviate from the trend of increasing yield with herbicide application. It is believed that yield for this curve in 2012 was affected by agronomic responses other than increased weed control. Lodging ratings were greater than those recorded for the recommended seeding rate at one of the two locations in 2012 (data not shown). Disease was also much more severe in the 560 plants m^{-2} treatment than any other treatment at both locations in 2012. Furthermore foliar disease severity was high in the herbicide rates that tended to provide mustard control without crop damage; 0.94, 1.87, and 3.75 g ai ha^{-1}. It is speculated that the increased seeding rate was able to provide adequate mustard control without herbicide application and produce equivalent seed yield in the unsprayed plots (Table 4.4). Rates of herbicide greater than 3.75 achieved greater mustard biomass reduction at the 560 plants m^{-2} rate (Figure 4.1), however crop injury, lodging, and disease increased in these plots and probably reduced crop yield more than uncontrolled mustard would have. The 560 plants m^{-2} rate in either year did not generally yield as high as the 140 and 280 plants m^{-2} rates and this is likely also explained in part by the effect of intraspecific competition among the lentil plants. Reduction of yield due to intraspecific competition at high seeding rates has been documented in previous literature (Forbes and Watson 1992).

Table 4.4 Foliar disease severity ratings in 2012. Means with different letters within columns are significantly different.

Fluthiacet Methyl Rate (g ai ha^{-1})	Foliar Disease Severity Rating (%)			
	Seeding Rate (plants m^{-2})			
	70	140	280	560
0	1.5	1.1	5.3 AB	17.4 BC
0.94	1.0	2.2	9.0 BC	25.3 CD
1.87	1.6	5.0	11.8 BC	33.2 D
3.75	1.9	3.0	15.7 C	32.6 D
7.5	1.3	4.5	9.4 BC	20.6 BC
15	2.2	2.2	8.6 BC	14.3 B
30	1.1	2.2	2.3 A	4.6 A
P value	0.9567	0.3300	0.0169	0.0002

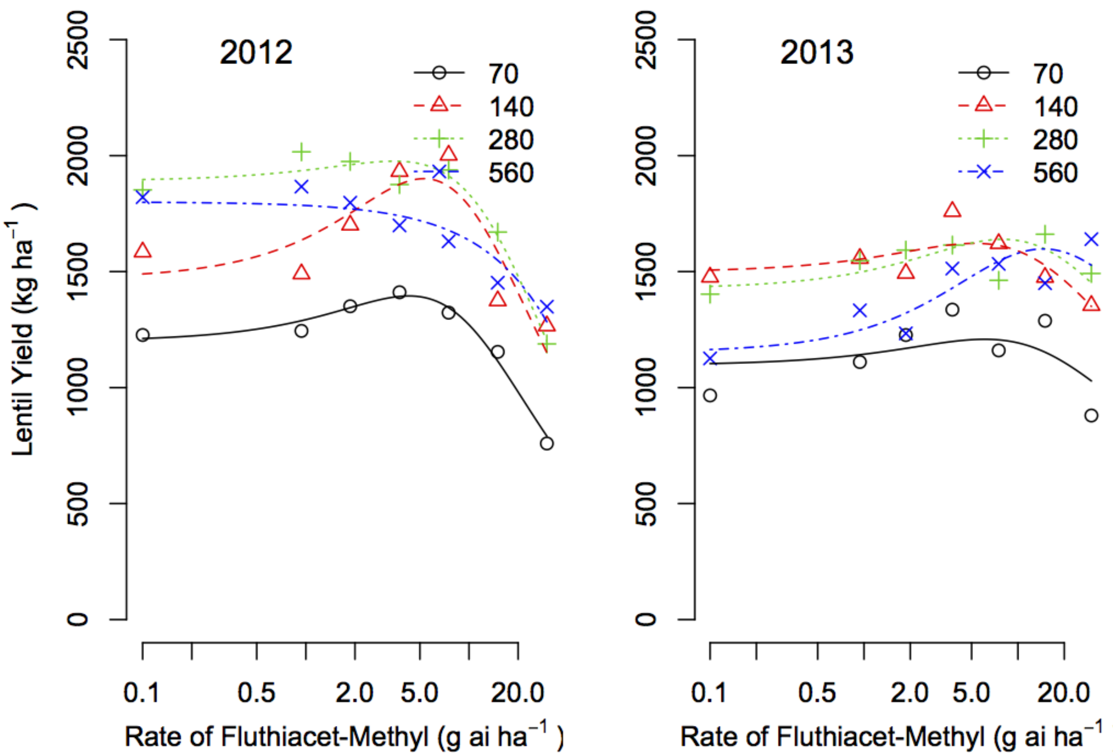

Figure 4.4 Lentil seed yield models for 2012 and 2013 indicate a general trend of yield increasing until rates of fluthiacet-methyl exceed 7.5 g ai ha^{-1}. Model lack of fit test statistics for 2012 and 2013 yield models are 0.7023 and 0.8537 respectively. Curves indicate seeding rates (plants m^{-2}).

Table 4.5 Parameter estimates for lentil yield models in 2012 and 2013. Standard errors are shown in brackets.

Parameter	Seeding Rate (plants m^{-2})	2012	2013
d	70	1199 (102)	1096 (94)
	140	1468 (98)	1498 (90)
	280	1890 (96)	1426 (91)
	560	1800 (60)	1151 (111)
b	common	1.58 (0.15)	1.26 (0.22)
e	70	10.5 (5.5)	13.9 (15.3)
	140	9.5 (3.0)	13.9 (15.3)
	280	17.9 (10.6)	13.9 (15.3)
	560	195.5 (391.0)	13.9 (15.3)
f	70	124.1 (101.8)	88.0 (118.6)
	140	222.3 (97.3)	113.5 (151.6)
	280	66.9 (80.9)	128.2 (157.1)
	560	-15.0 (8.4)	146.6 (161.8)

4.3.5 Economic Analysis

Yield data was analyzed by year and it was found that the greatest economic return was achieved when lentils were seeded at the 140 plants m^{-2} rate and fluthiacet-methyl herbicide was applied at 7.5 g ai ha^{-1} in 2012 and 3.75 g ai ha^{-1} in 2013 (Table 4.5). In 2012 returns with the recommended seeding rate dropped dramatically when application rates were lower than 3.75 g ai ha^{-1}. At herbicide rates of 1.87 and 0.94 g ai ha^{-1} returns were greatest when lentils were seeded at 280 plants m^{-2} in 2012. In 2013 the 140 plants m^{-2} rate maximized returns even at 0.94 and 1.87 g ai ha^{-1}. This indicates that if herbicides efficacy is compromised enhancing weed control with increased seeding rate can be a useful tactic to maintain profits. Due to the increased seed cost associated with large green lentils there may not be a benefit to increasing seeding rates when growers have confidence that herbicides will provide efficacious weed control.

Table 4.6 Net profits in $ per hectare were greatest with recommended seeding rate and when fluthiacet methyl was applied at a rate that provided efficacious weed control.

Year	Rate fluthiacet-methyl (g ai ha^{-1})	Net Profit ($ ha^{-1})			
		Seeding Rate (plants m^{-2})			
		70	140	280	560
2012	0	485.00	598.98	634.38	463.63
	0.94	492.44	557.91	703.89	483.20
	1.87	537.23	647.32	686.11	452.80
	3.75	562.28	745.61	643.38	410.44
	7.5	523.15	774.38	668.64	380.04
	15	448.77	503.58	551.58	306.15
	30	274.80	452.31	340.26	248.58
2013	0	429.09	637.30	523.00	231.48
	0.94	498.65	676.06	592.56	331.60
	1.87	554.69	644.52	614.44	283.10
	3.75	607.13	773.23	624.28	418.04
	7.5	520.63	704.76	529.24	426.57

15	579.97	631.62	643.00	383.51
30	376.76	567.60	518.31	470.40

Increasing seeding rate in large green CDC Improve lentil beyond the 140 plants m^{-2} rate did not result in increased maximum yields when fluthiacet-methyl was applied at a rate of 3.75 g ai ha^{-1} or more in 2012. In 2013 the 280 plants m_{-2} seeding rate occasionally achieved slightly greater yield than the 140 plants m^{-2} rate, but not with any pattern or regularity. These results indicate that although increasing seeding rate may help to achieve superior weed biomass reduction, this will not definitively result in increased yield, particularly if herbicides can be applied at rates that provide good weed control. Yield increases may be achieved in some years with increasing seeding rate if no herbicide is applied, or if herbicide efficacy is poor. A herbicide such as fluthiacet-methyl, that can cause significant crop injury with the current level of group 14 tolerance in lentil germplasm, may only be an option in lentil if usage rates are kept quite low, which would result in low efficacy on wild mustard. Although the low efficacy at these rates would not be adequate to warrant registration of the product for control of wild mustard, the product is showing encouraging results in kochia at rates as low as 2 g ai ha^{-1} (Ken Sapsford, personal communication). Therefore increasing seeding rate could represent a practice that could interact with lower rate fluthiacet-methyl application to better control wild mustard and ensure that yields are maintained. Increasing seeding rate to the 560 plants m^{-2} rate demonstrated that at a certain point increases in crop density will negatively influence crop yield even though weed control may be improved. Agronomic problems associated with excessive crop density observed in this study were increased lodging and disease severity (data not shown).

4.4 Conclusion

The differences in the two years of data demonstrate that herbicide efficacy is highly dependent on environmental conditions that are hard for producers to predict, and that increasing seeding rate can be a useful tactic to help mitigate this risk. In 2013 the herbicide appeared to have a greater phytotoxic effect on both the crop and weed. The better efficacy resulted in the ED_{50} not being lowered and lentil yield not being improved with increasing seeding rate in 2013. These results indicate that when herbicides effectively control weeds increased seeding rates may not be beneficial. However, increased seeding rate was able to maintain yield at lower application rates and maintain reasonable ED_{50} levels in 2012 when the herbicide did not seem to be as phytotoxic, and ED_{50} levels were much higher at lower seeding rates. These results show that by integrating the cultural practice of increasing seeding rate, producers can help ensure weeds are managed more effectively and can expand the usefulness of herbicide chemistries.

5 General Discussion

The objective of this research was to study an integrated weed management system and examine the interaction of the components of this system. Specifically the research looked to develop recommendations for lentil producers dealing with Group 2 resistant wild mustard in IMI tolerant lentil crops. More generally we wanted to examine the ability to manage weeds using a system that did not rely heavily on any single weed control tactic, but utilized multiple tactics to create a robust system.

5.1 Integrated Weed Management in Lentil

The first study tested an IWM system that combined cultural, mechanical, and herbicidal weed control tactics to control Group 2 resistant wild mustard in extra small red lentils. We hypothesized that this system would be able to provide weed control and produce yield equal to that of a system that relied only on herbicides for weed control. The results of this study largely proved our hypothesis. The fully integrated weed control system combined with increased seeding rate exhibited yields that did not differ statistically from the full herbicide system. The integrated treatment was also typically most profitable when seeded at the highest seeding rate, but it is unlikely that producers would be willing to adopt such a high seeding rate.

The results of this study show that the optimum seeding rate is dependent on the weed control method applied. The fully integrated and mechanical weed control systems demonstrated the greatest positive interaction when combined with increased seeding rate. If a full herbicide method is chosen, there is no statistically significant advantage to increasing seeding rate. Application of the full herbicide method would mean utilization of two additional herbicide modes of action to control the Group 2 resistant wild mustard and some may see this as an 'integrated' method as it does not rely on one herbicide mode of action for control. This interpretation should be cautioned against, as the method describes integrated herbicide management rather than true integrated weed management (Harker et al.

2012). The advantages of using a fully integrated method that combines the cultural practice of increasing seeding rate and mechanical weed removal with an integrated herbicide management approach may not seem tangible, as yield using this system was not greater than using the full herbicide system. The integrated system would also require the producer to handle a larger volume of seed at seeding time and spend more time monitoring weed emergence to achieve the relatively precise timing for efficacy of the rotary hoe. The integrated system may be more labour intensive for the producer, but it can provide comparable weed control and yield to the full herbicide system whilst being more resilient against failure of any single weed control tactic and buffering against selection pressure for herbicide resistant weeds. These are benefits that producers who employ these types of systems will see in the long term.

The mechanical weed control method utilized in the IWM study was the rotary hoe. The rotary hoe has been noted to experience reduced efficacy in specific environmental conditions, and these conditions were observed in our study. The rotary hoe has been noted to lose efficacy in wet conditions; both when the soil is wet and limits movement of the implement, and when rainfall is experienced following rotary hoeing, as weeds will fail to die due to desiccation (Mohler 2001b). These conditions were experienced in both 2012 and 2013 in Saskatoon (personal observation). In addition soil compaction limits efficacy of the rotary hoe. In 2013 compaction was observed by the researcher to reduce efficacy of the rotary hoe. Weed biomass reduction with the rotary hoe was not significantly greater than the control. Despite the failure of the rotary hoe to significantly reduce mustard biomass on its own, we observed the ability of the rotary hoe to interact favourably with other tactics, such as increased seeding rate, to provide greater weed biomass reduction and increased crop yield. The rotary hoe shows great potential to fit in an integrated weed control system for producers who have adopted minimum tillage practices. Presence of a mechanical weed control treatment is an important component of a truly integrated weed management system and should not be overlooked.

5.2 Seeding Rate Influence on Dose Response of Wild Mustard to Fluthiacet-Methyl

The dose response study confirms that the cultural practice of increasing seeding rate can interact with herbicide application to shift the parameters of the dose response curve and result in improved weed control. In terms of weed biomass reduction, the positive influence of increased seeding rate on reducing biomass when herbicides are not applied or are applied at low rates was observed at every site-year of the study. Furthermore ED_{50} value was significantly lower in 1 of the 2 years of study when seeding rate was increased. However yield was greater with increased seeding rates at low herbicide rates in only 1 of the 2 years of the study. This result indicates that although crop competition is able to consistently reduce weed biomass this does not necessarily translate into improved yields. The study also highlights that herbicides do not always provide consistent weed control in different years under differing environmental conditions. It shows that increasing seeding rate can be a reliable and effective way of insuring that weed control and yields are maintained when chemical control fails to perform as expected, even in a crop like lentil which is widely considered to be very weakly competitive (Sarker and Erskine 2006, Swanton and Weise 1991). These results highlight the importance of including cultural control methods, such as increased crop density, in integrated weed management systems.

5.3 Future Research

The fact that the extra small lentils in the IWM study experienced an advantage in weed control, and often yield, at seeding rates greater than the current recommendation suggests that producers should consider increasing seeding rate in conventional lentil production. This result contradicts the current common thinking that increasing seeding rate in lentil beyond the recommended seeding rate will lead to severe agronomic and disease problems and reduce yields. Even in an extremely wet site year (KCRF 2012) we did not observe any yield loss with increased seeding rates in extra small red lentils. However it is important to note that this study focused on weed control and was not a pathology study. Although these results are encouraging, they did not thoroughly examine the influence of increased seeding rate on the impact and severity of common lentil diseases. In addition, although seed yield was not decreased, this study did not attempt to assess seed quality, and it is quite possible that increased disease severity at the higher seeding rates may have lead to reduced seed quality and resulted in downgrading. Future studies that assess the impact of increasing seeding rate of different seed size classes of lentil on disease infection rate and severity would be a great asset to the knowledge base in this area.

It is interesting, though perhaps not unexpected, that the experiment conducted using extra small red lentils saw a greater advantage to increasing seeding rate than did the experiment conducted using large green lentils. Although the treatments were vastly different and the results cannot be directly compared, it is nonetheless worthwhile to think about this observation. The first lentils widely grown in Saskatchewan, and the lentils that would likely have been considered when developing the initial recommended seeding rates, were the large green variety Laird. The thousand kernel weight of Laird is 67 g per thousand which is equal to the TKW of CDC Improve lentil used in the dose response study (SSGA 2013) . The TKW of CDC Impala is 31 g per thousand, which is less than half the TKW of the large green varieties Laird and Improve (SSGA 2013). Thus it should not be surprising that the recommended seeding rate is better suited to growing lentils that are similar in seed size to Laird than it is to those that are less than half their size. Research in numerous other crops, including oat, wheat, and soybean, has shown that larger seeds are more capable of competing against weeds and reducing weed biomass than smaller seeds (Place et al. 2011, Willenborg et al. 2005, Xue and Stougaard 2002). Given this information it seems likely that the recommended lentil seeding rate should be adjusted for the small and extra small seed size classes.

A study that examines the influence of increased seeding rate on performance of the various lentil seed size classes would benefit lentil growers in making their seeding rate decisions.

5.4 Final Remarks

In a chapter published in 1994 discussing strategies to deal with herbicide resistance, J.M. Matthews observes that a benefit of the daunting problem of herbicide resistant weeds is that it has brought to light the fact that no single weed control technique is likely to provide continued control when used exclusively (Matthews 1994). This chapter is among many works published two decades ago indicating that multiple tactic weed control is the only feasible way to deal with herbicide resistant weeds (Powles and Matthews 1992, Swanton and Weise 1991, Thill et al. 1994). More recent work in management of resistant weeds continues to advocate for the importance of integrated management strategies in sustaining crop production (Anderson 2005, Beckie 2006, Blackshaw et al. 2008, 2002, Harker and O'Donovan 2013, Harker et al. 2009, O'Donovan et al. 2007, Swanton et al. 2008). Despite the impressive and convincing body of work published espousing the benefits of integrated strategies, weed control strategies reliant strictly on herbicides continue to be the favoured method of producers, and the instances of herbicide resistant weeds continue to grow (Heap 2014b). This thesis produced specific data regarding optimum lentil seeding rates, as well as a specific integrated strategy for lentil producers dealing with Group 2 resistant wild mustard. This will be useful information for growers seeding the estimated 900 000 hectares of lentil annually in Saskatchewan (SMA 2013a). However, it is the hope of the author that it also made a small contribution to the general idea that multi tactic weed management strategies are vital to continued sustainable weed control and profitable crop production. Use of cultural and mechanical weed control tactics, once common in agriculture, have now largely been relegated to organic production and viewed as archaic management practices, useful only to those with no technologically superior options. Those of us with the unique opportunity to generate research and disseminate research findings to producers should continue to study and communicate the effectiveness and importance of these weed control tactics and their role in integrated weed management strategies. It seems clear that they will need to become more prevalent in the future.

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