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ABSTRACT

Lentil is an important pulse crop in Saskatchewan. Weed control is central to lentil production due its poor competitive ability and the few herbicide options for use on conventional varieties. Imidazolinone tolerant lentil varieties have been developed to improve herbicidal weed control and crop safety. Two studies were conducted in 2006 and 2007 in Saskatchewan with the research objective of determining the optimal weed control timing and herbicide to maximize weed control and lentil yield. The first experiment investigated the critical period of weed control (CPWC) for lentil. The CPWC was realized by investigating two components; the duration of weed interference and the duration of the weed-free period which respectively determine the beginning and end of the CPWC. The crop remained weedy or weed-free from zero to eleven lentil nodes to investigate the durations of weed interference and weed-free period. There was an inverse relationship between weed biomass and lentil yield such that lentil yield was highest when weed biomass was minimal. The CPWC was found to commence at the five node stage and continue to the ten node stage. The second experiment investigated imazethapyr / imazamox, imazamox and metribuzin + sethoxydim applied at two application times to determine the best herbicide for the CPWC. The results indicated that imazethapyr / imazamox and imazamox applied at the six node stage resulted in the overall lowest weed biomass and highest lentil yield compared to application at the two node stage. In accordance with these results and the CPWC, imazethapyr / imazamox or imazamox should be applied at or before the five to six node stage to maximize lentil yield and minimize weed biomass.

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DEDICATION

I would like to dedicate this thesis in memory of my Grandpa Mike whose love of agriculture, passion for life, humility and, of course, sense of humour continue to inspire me.

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LIST OF ABBREVIATIONS

AAFC	Agriculture and Agri-Food Canada
ALS / AHAS	Acetolactate synthase /Acetohydroxyacid synthase
BASF	BASF Canada (Research Farm)
CDC	Crop Development Center
CL	Clearfield®
CPWC	Critical period of weed control
DNA	Dinitroanaline
GDD	Growing degree days
HT	Herbicide tolerant
IMI	Imidazolinone
KCRF	Kernen Crop Research Farm
PAR	Phytosynthetically active radiation
PM	Physiological maturity
POST	Post-emergent
PRE	Pre-emergent
SMA	Saskatchewan Ministry of Agriculture
SPG	Saskatchewan Pulse Growers
SSGA	Saskatchewan Seed Growers Association
TWR	Time of weed removal
WAE	Weeks after emergence
WFP	Weed-free period

1.0 Introduction

Lentil (*Lens culinaris* Medik.) is one of the earliest domesticated plants known to humanity (Sarker and Erskine, 2006). The crop is important for human nutrition and sustains large populations in south Asia and the Mediterranean region. Lentil is a relatively new crop to Saskatchewan. It was first introduced in 1969 (Slinkard et al. 1990) and since then has been widely adopted by producers. Canada is one of the world's largest lentil producers and exporters (Statistics Canada, 2010). Saskatchewan produces between 95 and 99% of the total amount of lentil produced in Canada (McVicar et al. 2006; AAFC, 2004).

Over the past 30 years many agronomic improvements to lentil have been made such as improved disease resistance, height, lodging tolerance and yield potential (Sarker and Erskine, 2006). However, weed control is a major concern and one of the greatest limiting factors in lentil production (Erman et al. 2004). Weed competition has resulted in lentil yield losses of 14 up to 100% (Swanton et al. 1993; Boerboom and Young, 1995; Singh et al. 1996; Mohamed et al., 1997; Curran et al. 1987; Elkoca et al. 2004). Lentil is a poor competitor with weeds due to its short stature, slow canopy closure and slow rate of development, especially early in the growing season (Elkoca et al. 2004; Kirkland et al. 2000; Blackshaw et al. 2002). As a result, lentil is ranked as the least competitive crop grown in western Canada.

Few herbicide options are available for post-emergent (POST) broadleaved weed control in lentil. Metribuzin is the only POST herbicide registered for broadleaved weed control in conventional lentil (SMA, 2008). However, metribuzin is known to have variable efficacy (Malik and Townley-Smith, 1990) and cannot be applied in combination with a gramincide (SMA, 2008). Metribuzin has also been observed to be phytotoxic to the lentil crop (SPG, 2000) and must be applied before the four node stage to minimize injury. The application period for metribuzin is short and weed control must be conducted within this period to ensure yield losses due to phytotoxicity of the herbicide do not occur.

To address weed control and crop selectivity concerns, plant breeders at the University of Saskatchewan Crop Development Center developed herbicide tolerant lentil varieties (Chant, 2004). Imidazolinone (IMI) tolerant lentil varieties were first commercially introduced in 2006. These varieties have increased tolerance to IMI herbicides until the 11 node stage. Imazethapyr / imazamox and imazamox are the IMI herbicides registered for use in IMI-tolerant lentil. IMI tolerance represents a new technology for weed control in lentil and information is required to optimize weed control and subsequently maximize yields.

The critical period of weed control (CPWC) defines the period in a crops life cycle in which weeds must be controlled to prevent yield losses and is a useful tool to determine the optimal timing of weed control (Knezevic et al. 2002). In practical terms, the CPWC is used to determine the length of time that weeds must be controlled in a crop to prevent significant yield loss. The CPWC has been determined in many crops and has helped producers to identify the optimal weed control timing and method. The CPWC has been determined for lentil (Mohamed et al. 1997; Singh et al. 1996) however, this research was conducted in vastly different environments than western Canada and the results cannot be used in this region.

The herbicide application systems in conventional lentil and IMI-tolerant lentil are different. Metribuzin is the only POST herbicide available for control of broadleaved weeds in conventional lentil (SMA, 2008). However, the weed control efficacy and crop phytotoxicity of metribuzin is variable (Malik and Townley-Smith, 1990; SPG, 2000) and it has a short optimum application period (SMA, 2008). Imazethapyr / imazamox and imazamox provide improved weed control efficacy and are safe to use on IMI-tolerant lentil varieties until the 11 node stage. Now that more efficacious herbicides are available and crop safety is not an issue, weed control in lentil will likely change. Comprehension of the CPWC will increase the understanding of lentil-weed competition and will enable lentil producers to optimize weed control timing to maximize yield. However, more information is needed to fully understand herbicide timing for weed control in relation to the CPWC for lentil.

The primary hypothesis for this thesis was that herbicides can be used to maintain lentil weed-free throughout the CPWC. Furthermore, it is believed that by delaying initial weed control beyond recommended conventional herbicide application staging that the efficiency of weed control in lentil would increase. The secondary hypothesis was that delayed timing of imazethapyr / imazamox application would result in the lowest weed biomass and highest lentil yield due to increased residual weed control. Therefore, the objectives of this research were:

1) To determine the CPWC for lentil in western Canada to optimize the timing of weed control.

2) To determine the best herbicide and application timing to keep lentils weed-free for the CPWC.

The ultimate goal of this research was to determine the optimal weed control timing and herbicide to maximize lentil yield for lentil grown in western Canada.

2.0 Literature Review

2.1. Lentil

2.1.1. Lentil background

Lentil (*Lens culinaris* Medik.) is an annual diploid (2n=14) originating from the Fertile Crescent of the Near East (Sarker and Erskine, 2006). The genus *Lens* belongs to the family Leguminosae, Sub-family Papilionaceae and is in the tribe, Vivieae. Lentil is one of the earliest domesticated plants known to man and is important for human nutrition. It is a cool season crop with moderate resistance to drought and high temperatures (Nielsen, 2001) and is grown during the winter season in Mediterranean and south Asian climates (Mohamed et al. 1997). Lentil seeds are an important source of protein, minerals (K, P, Fe and Zn) and vitamins and the crop sustains large human populations especially throughout south Asia and the Mediterranean region (Sarker and Erskine, 2006).

2.1.2. Lentil description

The lentil plant is a short, slender annual legume with a shallow rooting system (Sarker and Erskine, 2006). Lentil varieties grown in western Canada range in height from approximately 30 to 40 cm (SSGA, 2007). The plant first develops two scale nodes which typically remain under the soil surface. It then produces true leaves starting at the third node. Lentil plants typically develop new nodes and leaves approximately every four to five days under western Canadian environments.

Lentil is classified according to seed size, seed coat and cotyledon color (SSGA, 2007; McNeil et al. 2007). Chilean lentil is large seeded with a thousand seed weight of 50 grams or greater while Persian lentil is small seeded with a thousand seed weight of 40 grams or less (McVicar et al. 2006). The major seed coat classes of lentil are green and red (SSGA, 2007; McNeil et al. 2007). Green lentil generally has a pale seed coat and yellow cotyledons whereas red lentil has dark seed coats and red to orange cotyledons. Green lentil is typically marketed as a whole seed, while red lentil is marketed either whole or dehulled and split. Red lentils have become the predominant market class grown in Saskatchewan and in 2009 comprised over 50% of total lentil acres (SMA, 2010).

2.1.3. Lentil production

Lentil was first introduced into Saskatchewan in 1969 (Slinkard et al. 1990) and in 1970 approximately 600 hectares were grown (McVicar et al. 2006). Through breeding and agronomic improvements, lentil acreage has increased drastically and in the 2009 growing season over 950,000 hectares were in production (Statistics Canada, 2010). Saskatchewan produces approximately 95 to 99% of the lentil crop in Canada with Alberta and Manitoba producing the remainder (AAFC, 2004; McVicar et al. 2006). Lentil is largely grown in the brown and dark brown soil zones as well as the thin black soil zone of Saskatchewan, when moisture is not excessive (McVicar et al. 2006). Average lentil yields in Saskatchewan are approximately 1180 kg ha^{-1}.

Canada is among the top two producers of lentil in the world and also leads the export market (AAFC, 2004). Other major lentil producing countries include India, Turkey, Syria, Australia, Nepal and the United States (Sarker and Erskine, 2006). Major importing countries include Spain, Colombia, Egypt, Algeria, Sri Lanka, France, Pakistan, Bangladesh and India.

2.2. Weed Control Issues in Lentil

2.2.1. Lentil and weed competition

Weeds are a major concern and weed control is a foremost issue in lentil production. In fact, Erman et al. (2004) consider weeds as the most important factor affecting lentil yield. Weeds compete with the crop for nutrients, soil moisture, light and space and may also harbour insects, pests and pathogens that can affect the lentil crop (Brand et al. 2007). Weed competition can cause lentil yield losses ranging from 14 to 100% (Swanton et al. 1993; Boerboom and Young, 1995; Singh et al. 1996; Mohamed et al., 1997; Curran et al. 1987; Elkoca et al. 2004) and can also cause problems for mechanical harvest (Brand et al. 2007).

Lentil is generally regarded as a poor competitor with weeds (Sarker and Erskine, 2006; Tepe et al. 2004; Mohamed et al. 1997; Singh et al. 1996; Erman et al. 2004). The physiological and morphological factors that generally increase the competitive ability of a crop with weeds include: early emergence, rapid leaf expansion, the formation of a dense canopy, increased plant height, early vigorous growth and increased root size (Blackshaw et al. 2002). Unfortunately, lentil does not possess many of these aforementioned properties. Lentil develops relatively slowly, especially early in the growing season, which creates the opportunity for the growth and development of weeds (Erman et al. 2004; Elkoca et al. 2004; McDonald et al. 2007). The lentil canopy closes late in comparison to other crops and is often sparse with open space available for weeds to establish (Elkoca et al. 2004; Kirkland et al. 2000). Lentil is also a short plant (Elkoca et al. 2004) reaching heights of only 30 to 40 cm (SSGA, 2007) and, combined with open canopy structure, provides little shade and increased opportunity for weed emergence. Lentil roots are relatively shallow which allow moderate drought resistance; however, this limits the uptake of water and nutrients when in competition with weeds (McVicar et al. 2006). Furthermore, lentil does not tolerate water-logged conditions or saline soils. Therefore, the combined physiological and morphological characteristics of lentil result in relatively low competitiveness with weeds.

2.2.2. Integrated weed management for lentil

Weed management is integral to ensure profitable lentil production due to the crops poor competitiveness with weeds. Successful and sustainable weed management involves the use of many forms of weed control. Cultural, physical and chemical methods are often employed to manage weeds in lentil crops (Brand et al. 2007). Brand et al. suggest that weed pressure should be minimized throughout the entire lifecycle and therefore the weeds should be controlled prior to seeding as well as at emergence, vegetative development, reproductive development and maturity. It is especially important to control weeds during the emergence and vegetative stages to prevent competition for nutrients, water and photosynthetically active radiation (PAR). Weeds that germinate and grow during the reproductive and maturity stages typically do not vigorously compete with the lentil crop (McDonald et al. 2007). However these late emerging weeds can cause issues with mechanical harvest and can result in yield loss or crop quality loss (Brand et al. 2007).

Weed control methods such as hand weeding (Elkoca et al. 2004) and physical control methods such as in-crop tillage (Boerboom and Young, 1995) are effective and commonplace in some lentil growing regions however they are labour intensive, time demanding and expensive. Therefore, herbicides are used extensively in lentil weed control programs in North America. Chemical weed control is an effective means of weed removal in most cropping systems. In lentil cropping systems both pre-emergent (PRE) and post-emergent (POST) herbicides can be used to control weeds. In western Canada there are many options for grass weed herbicides in lentil but few efficacious broadleaved herbicides are available (McVicar et al. 2006; Wall and McMullan, 1994).

2.3. Weed Control with Herbicides

2.3.1. Lentil herbicides

Weed management in lentil production is difficult due to the poor competitiveness of the crop and the availability of only a few efficacious herbicides for control of broadleaved weeds (Wall and McMullan, 1994). In addition, few herbicides are registered for control of both grass and broadleaved weeds in lentil despite a large amount of research devoted to this issue. PRE herbicides are often ineffective on late emerging cohorts of weeds and the available POST broadleaved herbicides can result in crop damage (McDonald et al. 2007).

There are currently three herbicides registered for control of broadleaved weeds in lentil, ethalfluralin ({*N*-ethyl-*N*-(2-methyl-2-propenyl)-2,6-dinitro-4-(trifluoromethyl) benzenamine}; trade name: Edge^{TM}), trifluralin ({2,6-dinitro-*N*,*N*-dipropyl-4-(trifluoromethyl) benzenamine}; trade name: Treflan^{TM}) and metribuzin ({4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5-(4*H*)-one}; trade name: Sencor^{TM}) (Senseman, 2007; SMA, 2008). Trifluralin and ethalfluralin are classified as dinitroanalines (DNA) and are mitotic inhibitors (group three) with activity on both grass and broadleaved weeds. DNA are PRE herbicides and affect roots and shoots of emerging seedlings resulting in the appearance of swollen root tips and shoots. These herbicides have limited activity on cruciferous weeds (Wall and McMullan, 1994) and their activity and efficacy can be influenced by soil and environmental conditions (Beckie et al. 2006). Furthermore, the application of these herbicides can result in recropping restrictions for some crops.

Metribuzin is classified as a photosynthetic inhibitor (group five herbicide) and affects only broadleaved weeds (SMA, 2008). The herbicide is foliar applied and has limited soil activity with a half life of only 2.6 weeks (Bouchard et al. 1982). The resulting injury includes chlorosis and necrosis of the oldest leaves within one to three days (Senseman, 1997). Metribuzin provides limited control of broadleaved weed species (Malik and Townley-Smith, 1990), suppressing wild mustard (*Sinapsis arvensis* L.), lambs quarters (*Chenopodium album* L.), and stinkweed (*Thalpsis arvense* L.) (SMA, 2008). Furthermore, metribuzin can be phytotoxic to lentil with symptoms including leaf drop, reduced yield and plant death (SPG, 2000). Metribuzin can also result in reduced lentil seed size (with possibly lower germination) (Malik and Townley-Smith, 1990). To prevent such injury metribuzin must be applied early in the growing season (McVicar et al. 2006) which may not correspond to optimal weed control timing. Furthermore, metribuzin cannot be applied in combination with graminicides due to antagonism of grass weeds (Kirkland et al. 1989). Graminicides must be applied approximately five to seven days after metribuzin (SMA, 2008). This delays grass weed control and is generally inconvenient and expensive for the producer to make two herbicide applications to control both grass and broadleaved weeds.

There are several graminicides registered for POST grass weed control in lentil including clethodim {(±)-2-[(*E*)-1-[(*E*)-3-chloroallyloxyimino]propyl]-5-[2-(ethylthio)propyl]-3-hydroxycyclohex-2-enone}; trade name: Select^{TM}, Centurion^{TM}) and sethoxydim {2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cylohexen-1-one}; trade name: Poast^{TM}), (Senseman, 2007; SMA, 2008). These herbicides are classified as group one and inhibit lipid biosynthesis. The resulting injury includes chlorosis of the youngest leaf and meristematic region. After a short time (approximately seven days) the meristematic region becomes completely necrotic and the leaf is easily pulled from the sheath.

Imidazolinone (IMI) herbicides (ie. imazethapyr, imazamox, imazamethabenz) have received attention for development in lentil weed control programs due to their use in other pulse crops including field pea (*Pisum sativum* L.). The IMI herbicides are classified as group two and inhibit the acetolactate synthase/acetohydroxyacid synthase (ALS/AHAS) enzymes which are involved in the production of the branched chain amino acids, valine, leucine and isoleucine (Tranel and Wright, 2002) and control a broad range of grass and broadleaved weeds (Shaner and Hornford, 2005). This class of herbicides is popular due to the low rates of active ingredient required for weed control, reduced environmental impact and low mammalian toxicity (Tan et al. 2005).

Imazethapyr and imazamox are the only IMI herbicides registered in western Canada (SMA, 2008). Imazamox is registered alone at 20 g ai ha^{-1} and imazethapyr is registered alone at 50 g ai ha^{-1}. Imazamox and imazethapyr are also registered in a 1:1 combination (30 g ai ha^{-1}).

Imazamox and imazethapyr differ in soil persistence (Aichele and Penner, 2005). Imazamox has a lower pKa value than imazethapyr and therefore imazamox is less likely to be adsorbed by the soil at any given pH. The most important factors for IMI soil adsorption are organic matter, pH and time (Shaner and Hornford, 2005). Increased organic matter and clay content as well as decreased soil pH result in increased soil adsorption of imazethapyr and to a lesser extent, imazamox. IMI herbicides are adsorbed less in soils with pH values from 6 to 9 and soil adsorption increases as the pH of the soil decreases. The concentration of imazamox and imazethapyr in the soil is also influenced by time. For example, the estimated half life of imazamox is 10 to 30 days whereas imazethapyr has an estimated half life of 45 to 112 days (Aichele and Penner, 2005; Shaner and Hornford, 2005). IMI herbicides dissipate in soil by microbial degradation therefore persistence in soil is also affected by soil moisture, temperature, soil texture and pH. Soil conditions that restrict microbial degradation retard IMI herbicide dissipation.

Imazamox and imazethapyr also differ in weed control (Blackshaw, 1998). Imazamox has increased control of grass weeds in comparison to imazethapyr (Blackshaw, 1998) and imazethapyr has increased broadleaved weed control (SMA, 2008). Research conducted investigating IMI herbicide application in lentil indicated that imazethapyr applied PRE did not result in lentil injury and provided effective weed control (Malik and Townley-Smith, 1990; Wall and McMullan, 1994). However, imazethapyr applied POST resulted in lentil injury. It was concluded that IMI herbicides should not be used POST in conventional lentil varieties.

2.3.2. Imidazolinone tolerant crops

Currently there are six herbicide resistant (transgenic and non-transgenic) crops grown in Canada; canola (*Brassica napus* L.), soybean [*Glycine max* L. Merr.], corn (*Zea mays* L.), wheat (*Triticum aestivum* L.) sunflower (*Helianthus annuus* L.), and lentil (Beckie et al. 2006; Tan et al. 2005). Herbicide resistant crops provide many benefits to producers including added herbicide options, longer application period through the crops life cycle, increased weed control and, potentially, increased economic return. Maize (*Z. mays* L.) tolerant to IMI's was commercialized in 1992 and was the first crop with tolerance to IMI herbicides (Tan et al. 2005). Other IMI-tolerant crops have been developed and include canola, rice (*Oryza sativa* L.), wheat and sunflower. IMI-tolerant lentil is one of the latest crops bred with this herbicide tolerance

(Chant, 2004; Beckie et al. 2006). Tolerance to IMI herbicides is derived from mutagenesis induced amino-acid substitutions that occur at the positions of Ala122, Pro197, Ala205, Trp574 and Ser653 (Tan et al. 2005). The majority of IMI-tolerant crops were developed from Ala205, Trp574 and Ser653 mutations alone or in combination which results in a reduction of the sensitivity of the AHAS enzyme to IMI herbicides. Crops tolerant to IMI herbicides are considered non-transgenic because they were developed through selection or mutagenesis which are considered conventional breeding methods.

Tolerance to IMI herbicides has proven to be beneficial in many crops. These benefits include increased control of difficult weeds that would otherwise go uncontrolled with conventional varieties (Tan et al. 2005). For example, red rice (*O. sativa* L.) is a common weed in rice production and causes yield loss when left uncontrolled. In conventional cropping systems there are no means of in-crop control of this weed. However, IMI herbicides are very effective against red rice in IMI-tolerant rice. Another benefit is increased efficaciousness of IMI herbicides compared to other herbicides used in conventional cropping systems. An example of this benefit is the control of wild mustard (*Sinapsis arvensis* L.) and stinkweed (*Thalapsi arvense* L.) in canola crops. Prior to herbicide resistant canola varieties, wild mustard and stinkweed were difficult to control with conventional herbicides due to the poor efficacy of registered products (ie. Muster^{TM}; SMA, 2008). IMI herbicides provide control of these troublesome weeds. Lastly, a benefit unique to IMI-tolerant crops is that there are fewer trade restrictions compared to transgenic herbicide tolerant or resistant varieties (Tan et al. 2005). IMI-tolerant crops are developed with conventional breeding methods and are non-transgenic. As such, they are not subject to trade barriers which preclude genetically modified crops.

2.3.3. Imidazolinone tolerant lentil

Much research has been devoted to developing IMI herbicides for use on conventional lentil varieties. However, due to the phytotoxic effect of IMI herbicides on conventional lentil they cannot be applied POST. The Crop Development Center (CDC) at the University of Saskatchewan saw this as an opportunity and developed lentil varieties tolerant to IMI herbicides, imazethapyr and imazamox (Holm and Vandenberg, 1998).

RH44, a medium green lentil genotype, was the first lentil genotype that possessed tolerance to IMI herbicides (Chant, 2004). Tolerance to IMI herbicides was derived through mutagenesis which resulted in a point mutation of a single nucleotide. The mutation caused an amino acid substitution in which a serine was substituted for an asparagine in the AHAS gene which conferred tolerance to IMI herbicides (US Patent 7232942, 2007). This tolerance was transferred to other lentil genotypes by conventional breeding techniques. CDC Imperial and CDC Impact are small and extra-small red lentil varieties and were the first Clearfield® (CL) lentil varieties commercialized (SSGA, 2007). They were released to growers in 2006. These varieties were developed by backcrossing the breeding line, RH44, with CDC Robin and CDC Blaze, respectively. The IMI-tolerant varieties therefore have very similar characteristics to commercially accepted varieties. Imazethapyr / imazamox and imazamox are registered for use on IMI-tolerant lentil (SMA, 2008). Both herbicides are registered for application until the six node stage however research indicates that the herbicides can be safely applied until the 11 node stage (Chant, 2004).

2.4. Crop-Weed Competition Models

2.4.1. Critical period of weed control

The CPWC is a concept which describes an interval in the crops life cycle in which weeds must be absent to prevent yield losses (Zimdahl, 1980). The CPWC was first documented by Nieto et al. (1968). Since its inception the CPWC has been determined for many crops including beans (*Phaseolus vulgaris* L) (Nieto et al. 1968; Kasasian and Seeyave, 1969), maize (Nieto et al. 1968), corn (Hall et al. 1992; Williams, 2006), soybean (Knezevic et al. 2003), canola (Martin et al. 2001), chickpea (*Cicer arietinum* L.) (Mohammadi et al. 2005), lentil (Mohamed et al. 1997; Singh et al. 1996), potato (*Solanum tuberosum* L.) (Ahmadvand et al. 2009) amongst others. The CPWC concept facilitates an understanding of a crop's competitive ability with weeds and has the potential to determine the appropriate time of weed control (Knezevic et al. 2002). The CPWC can be used to optimize herbicide application, tillage or other means of weed control. Therefore, utilizing the CPWC can reduce prophylactic herbicide usage, environmental and ecological degradation (Knezevic et al. 2002), as well as the cost of weed control (Mohammadi, 2005). The CPWC has been studied primarily to determine the appropriate timing of POST herbicides and with the rapid adoption of herbicide tolerant crops there is even more potential for its utility (Knezevic et al. 2002).

The CPWC is determined by measuring two separate competition components; the duration of weed interference, and the duration of the weed-free period required to prevent yield loss (Williams, 2006). The first concept measures the effect of the duration of weed interference on crop yield and is commonly referred to as the critical time of weed removal (TWR). The underlying concept of the duration of weed interference is that early season weed growth can be tolerated by a crop until a certain point in the crop’s life cycle after which any subsequent weed competition will result in yield loss (Knezevic et al. 2002). Significant yield loss does not occur before this point due to the small size of the crop and weeds, the space between them and the inherent lack of competition for resources such as light quantity, water and nutrients (Rajcan and Swanton, 2001; Zimdahl, 2004; Weaver and Tan, 1987). However, early weed growth can result in crop yield loss prior to the onset of resource competition. Rajcan et al. (2004) have shown that changes in light quality early in the growing season result in morphological changes in corn plants. The light quality changes were due to reflected light from the presence of weeds or pseudo weeds. The weeds did not result in a reduction in light quantity but did affect light quality by increasing the far-red:red light ratio. The increased far-red:red ratio resulted in increased corn height, leaf area and a higher root to shoot ratio. However, in theory, the same effect could occur from neighbouring corn plants as similar light quality competition would occur. Although both direct and indirect effects may cause yield loss in crops, the empirical measure of crop yield loss using the CPWC will account for both.

To study the effect of the duration of weed interference, the weeds are removed at sequentially increasing growth stages to determine the stage at which significant yield loss (usually 5%) begins to occur (Knezevic et al. 2002). This component defines the beginning of the CPWC and weed growth before this stage will not result in yield loss (Figure 2.1). Weed growth after the determined crop stage will cause irrevocable yield loss due to competition between the crop and the weeds.

Figure 2.1 Description of the duration of weed interference. Weed growth until the crop stage indicated by the arrow will not compete with the crop and if removed at that point will not cause yield loss. Continued weed growth after the indicated point will result in irrevocable yield loss.

There are many factors that can influence the beginning of the CPWC. Weed density affects the duration of weed interference by influencing the level of competition (Knezevic et al. 2002). That is, if weed density is low the competition for resources is lessened and weed interference will be tolerated later into the crop’s life cycle. Conversely, if the weed density is high, competition for resources is increased and the weeds must be removed earlier to prevent crop yield loss. The time of weed emergence may influence the duration of weed interference to a greater extent than weed density. Weeds that emerge before or at the same time as the crop are more competitive than weeds that emerge after the crop and therefore have a greater potential to cause yield loss (O’Donovan et al. 1985; Swanton et al. 1999). Therefore the beginning of the CPWC is a function of weed growth and the factors that influence weed competitiveness. Understanding this assists weed managers by describing the effect of weed density and emergence timing (Rajcan and Swanton, 2001).

The second component of the CPWC measures the duration of the weed-free period required to prevent yield loss (Knezevic et al. 2002; Williams, 2006). It is also referred to as the critical weed-free period (WFP). The required duration of the weed-free period is a function of the crop’s ability to resist late season weed competition. That is, it is the period after which newly emerged weeds will not cause significant yield loss. It is generally found to be late in the crop’s growth cycle and is a function of its ability to tolerate late emerging weeds. An understanding of the duration of the weed-free period required to prevent yield loss will assist weed managers by determining when weed control can be stopped without sustaining significant yield loss.

To study the effect of the duration of the weed-free period the crop is kept weed-free for sequentially increasing lengths of time to determine the stage at which weed emergence and growth cease to cause yield loss (Knezevic et al. 2002) (Figure 2.2). The weed-free period that is required to prevent yield loss represents the end of the CPWC. Weed growth after this time will not result in yield loss but weed growth before this time will cause irrevocable yield loss.

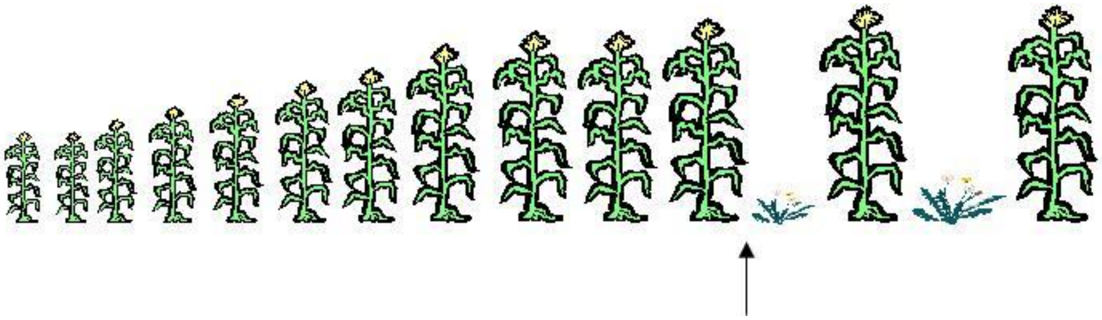

Figure 2.2 Description of the duration of the weed-free period required to prevent yield loss. Weed growth prior to the stage, indicated by the arrow, will cause yield loss. Weed growth after this stage will not cause yield loss.

The end of the CPWC is a function of the crops competitiveness (Zimdahl, 2004) and is influenced by crop size and canopy density (Blackshaw et al. 2002). Therefore, based on these attributes, the end of the CPWC varies for different crops. If the crop grows tall and produces a dense canopy the ability of weed seedlings to establish and grow is inhibited. Furthermore, as a result of the crops large size the crop has a competitive advantage for the uptake of limited resources and therefore suppresses the growth of weeds. Conversely, if the crop is short with an open canopy there will be more opportunity for weed emergence due to available light. Crop density is also important in dictating the duration of the required weed-free period. In theory, the higher the crop density the greater the ability for the crop to suppress weed growth (McDonald et al. 2007) shortening the weed-free period required to prevent yield loss. Conversely, the lower the crop density the greater the opportunity for weeds to emerge from gaps in the crop canopy which would result in a longer weed-free period.

The CPWC is realized once both the duration of weed interference and the duration of the weed-free period required to prevent yield loss are defined (Figure 2.3). Competition outside of the CPWC will not negatively impact crop yield (Knezevic et al. 2002). Therefore, the CPWC defines the period of the crops growth cycle that is most sensitive to weed competition (Rajcan and Swanton, 2001).

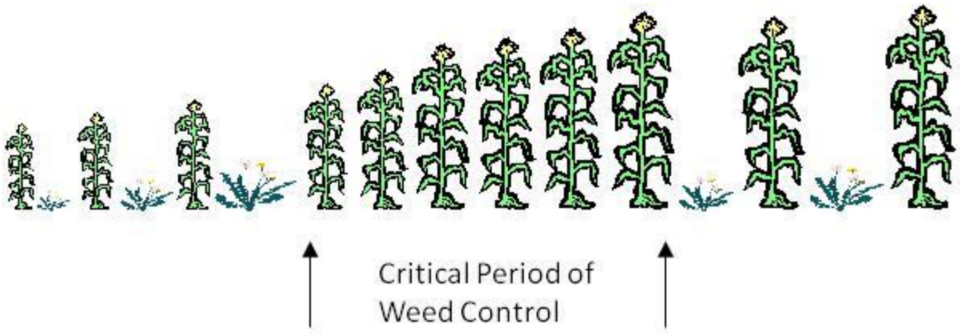

Figure 2.3 Description of the critical period of weed control (CPWC). Weed growth outside the crop stages, indicated by the arrows, will not impact yield.

The CPWC is not an absolute period for any crop (Zimdahl, 2004). As with other theoretical models, there are limitations. The CPWC is specific for each crop as a result of the differences in crop morphology, physiology and development (Rajcan and Swanton, 2001; Knezevic et al. 2002). The CPWC can also vary due to inconsistencies among environments which influence the competitive ability of the crop and weed species present. The CPWC can also vary due to the weed species present, the density and the time of weed emergence relative to that of the crop. Furthermore, management practices within the cropping system can influence the CPWC. Seeding date (Williams, 2006), soil nutrient supply (Evans et al. 2003), tillage system (Halford et al. 2001) and row spacing (Knezevic et al. 2003) are examples of cultural factors that can affect the CPWC.

The CPWC can be described using time, thermal time or crop development. For example, the CPWC has been measured in the numbers of days weeds were present and weeds were absent (Neito et al. 1968), days after planting (Mulugeta and Boerboom, 2000), days after emergence (Martin et al. 2001), weeks after planting (Gibson and Liebman, 2003), weeks after emergence (WAE) (Singh et al. 1996, Mohamed et al. 1997), growing degree days (GDD) after planting (Webster et al. 2007; Knezevic et al. 2003), GDD after emergence (Williams, 2006) and crop stage (Hall et al. 1992; Halford et al. 2001; Woolley et al. 1993). This has resulted in inconsistencies among studies and the inability to compare and contrast among different environments. Many authors argue that crop stage is the best indicator of the CPWC (Knezevic et al. 2002; Wooley et al. 1993; Ahmadvand et al. 2009). Woolley et al. (1993) suggests that crop stage should be used in order to facilitate crop management recommendations. According to Knezevic et al. a better understanding of the length of the CPWC can be achieved when the mechanism of competition is understood in terms of crop stage. Lastly, the use of crop growth stage as the main identifier of the CPWC allows comparisons to be made across different locations and environmental conditions (Ahmadvand et al. 2009; Knezevic et al. 2003; Van Acker, 1993).

2.4.2. Critical period of weed control for lentil

The CPWC has been studied for lentil in north-eastern Jordan (Singh et al. 1996) and Sudan (Mohamed et al. 1997). Singh et al. (1996) determined that the CPWC began at approximately five to six WAE and continued until 12 to 14 WAE. In contrast, Mohamed et al. (1997) determined that the CPWC started at two WAE and continued until four WAE at one location and from four until six WAE at another location. However, due to the inherent limitations of the CPWC (Knezevic et al. 2002; Rajcan and Swanton, 2001) and the inability to extrapolate the crop stage from WAE, the CPWC is considered to be unknown in western Canada. The climatic and geographic differences between Jordan and Sudan compared to western Canada are another reason that the results cannot be extrapolated. Lentil is grown in Jordan and Sudan's winter and matures into increasing temperatures and drought (Sarker and Erskine, 2006; Mohamed et al. 1997). In western Canada, lentil is planted in spring, grows predominately in the summer and matures in decreasing temperatures. Furthermore, the cultural practices are also vastly different between Jordan and Syria and western Canada. Throughout Jordan and Syria POST weed control was conducted by hand. Weed control in western Canada is typically accomplished with herbicides.

Components of the CPWC of lentil have also been studied. The effect of the duration of wild oat (*Avena fatua* L.) interference on lentil yield was studied in the Palouse region of Washington state by Curran et al. (1987). They determined that a shorter duration of interference of wild oats was tolerated with increased weed densities. However, this project did not consider the duration of the weed-free period and only accessed one weed thereby limiting the implications its application.

The CPWC is an important weed management tool for optimizing the timing of weed control, despite its limitations. The CPWC concept typically has been used to determine the best application timing for non-residual herbicides (Knezevic et al. 2002) however it may have implications for residual herbicides in lentil production. Lentil is sensitive to weed competition and requires a prolonged weed-free period (Singh et al. 1996; Mohamed et al. 1997) in which a herbicide with extended weed control would be advantageous. Hamill et al. (2000) compared residual and contact herbicides and confirmed that residual herbicides were able to provide increased control of weeds as indicated by lower weed biomass. This has implications for the application of imazamox and imazethapyr on IMI-tolerant lentil. Imazamox provides limited soil residual weed control (Shaner and Hornford, 2005) and therefore could be used in situations where there is a limited weed seed bank or when there is the potential for deleterious residual carry-over to following crops. Imazethapyr or a combination of imazethapyr / imazamox could be used in situations conducive to the use of increased soil activity and the potential for multiple cohorts of weeds. A residual herbicide applied at the beginning of the CPWC for lentil should maximize lentil yield and minimize weed biomass.

3.0 The critical period of weed control for lentil

3.1. Introduction

Lentil is an important crop throughout the world. It is used primarily as a food source in Middle Eastern and south Asian countries (Sarker and Erskine, 2006). Canada is one of the major producers and exporters of lentil globally and Saskatchewan produces 95 to 99% of Canada’s total production (AAFC, 2008). In 2009, Saskatchewan had over 950,000 hectares of lentil in production which resulted in 1.5 million tonnes of harvested product (Statistics Canada, 2010).

Weed control is a major limitation in lentil production (Erman et al., 2004) as lentil is ranked as one of the least competitive crops grown in western Canada (Swanton et al. 1993; Cessna, 1997; Blackshaw et al. 2002). Weeds cause many difficulties in lentil production due to the lentil plants short stature, slow rate of development and the crops slow canopy closure, (Blackshaw et al. 2002; Ball et al. 1997). Weeds can cause lentil yield losses as high as 100% (Erman et al. 2004) with early weed growth being the most detrimental to yield (Mohamed et al. 1997). Control of weeds is necessary for profitable production (Cessna, 1997). However, lentil production is further limited by the lack of efficacious post-emergent (POST) herbicides (Wall and McMullan, 1994). Currently metribuzin is the only POST broadleaved weed herbicide registered for use in conventional lentil. However, metribuzin is known to be injurious to the crop (SPG, 2000; Friesen and Wall, 1986) and can result in stunting, yellowing, leaf drop and subsequent yield loss. Metribuzin has limited control of many of the economically important broadleaved weeds in lentil. Metribuzin must be applied early (one to four node stage) to lentil to avoid crop injury. Furthermore, metribuzin cannot be combined with graminicides in a single application due to antagonism of grass weeds (Kirkland et al. 1989) therefore weed control usually requires two herbicides applications.

Due to the shortcomings of metribuzin, many lentil producers use an unregistered, reduced rate of imazethapyr applied pre-emergent (PRE) to control broadleaved weeds. Imazethapyr is not registered in the brown and dark brown soil zones (SMA, 2008) due to carry over issues to crops seeded one year after application (Curran et al. 1991; Blackshaw, 1998). The use of unregistered herbicides could have deleterious effects on lentil as well as future crops and could also cause environmental, regulatory and trade issues.

Plant breeders at the University of Saskatchewan realized the weed control constraints in conventional lentil production and developed lentil varieties tolerant to imidazolinone (IMI) herbicides including imazethapyr / imazamox and imazamox (Chant, 2004; SMA, 2008). Imazethapyr / imazamox and imazamox control many of the economically important broadleaved and grass weeds (Ball et al. 2003; Blackshaw, 1998) in Saskatchewan and can be applied over a wider range of crop stages than metribuzin (SMA, 2008).

Metribuzin is registered for application up to the four node stage in lentil (SMA, 2008), however in practice, lentil producers often apply it earlier in order to avoid crop damage. Imazethapyr / imazamox and imazamox are registered up to the six node stage in IMI-tolerant lentil however, Chant (2004) found that application of imazethapyr / imazamox until the 11 node stage (early flowering) did not have a negative effect on flowering, crop biomass, or crop yield. Lentil producers may be accustomed to early herbicide application in lentil from years of metribuzin application and may be applying imazethapyr / imazamox too early. However, the optimum timing of herbicide application is not well defined.

The critical period of weed control (CPWC) is a theoretical concept that can determine the appropriate timing of weed control in a crop (Williams, 2006; Mulugeta and Boerboom, 2000). The CPWC is the interval in the crops growth cycle in which weeds must be controlled to prevent yield losses (Nieto et al. 1968; Kasasian and Seeyave, 1969; Knevezic et al. 2002). It is realized by measuring two separate components, the duration of weed interference (also known as the critical time of weed removal (TWR)) and the duration of the weed-free period (also known as the critical weed-free period (WFP)). Combined, these components constitute the CPWC in which weeds must be controlled to prevent significant yield losses.

The duration of weed interference defines the beginning of the CPWC and is determined by the time at which weed interference begins to cause significant yield loss (Knezevic et al. 2002). Thus, the beginning of the CPWC is the time at which weeds must be removed to prevent weed loss. Weed growth prior to the onset of the CPWC should not result in yield loss because both the crop and the weeds are too small to compete for resources (Radosevich et al. 1997; Norsworthy and Oliveira, 2004).

The end of the CPWC is defined by the duration of the weed-free period which is the length of weed-free conditions required to prevent significant yield losses from late emerging weeds (Knezevic et al. 2002). This period ends when the crop is large enough and significant yield losses from newly emerged weeds does not occur (Radosevich et al. 1997).

The CPWC has been determined in many crops grown in western Canada including chickpea (Mohammadi et al. 2005), canola (Martin et al. 2001), soybean (Knezevic et al. 2003; Halford et al. 2001), corn (Hall et al. 1992; Halford et al. 2001; Williams et al. 2006) and lentil (Singh et al. 1996; Mohamed et al. 1997). The CPWC of lentil was found by Singh et al. (1996) to begin between at approximately five to six weeks after emergence (WAE) and continue until 12 to 14 WAE in Jordan. In Sudan, Mohamed et al. (1997) determined that the CPWC started at two WAE and continued until four WAE at one location and four to six WAE at another location. However, the results from these studies are not applicable to western Canadian lentil production as the environment, growing conditions and weed populations in Sudan and Jordan are vastly different than in western Canada. In these locations lentil is produced in the cool winter months whereas in western Canada they are grown in the spring and summer months. Singh et al (1996) and Mohamed et al. (1997) also used WAE as the measurement criteria instead of crop stages, which is impossible to compare to western Canadian agriculture as the development rate of lentil would differ.

The objective of this research was to determine the CPWC for lentil in western Canada to optimize the timing of weed control. Understanding the CPWC will provide insight into the timing of herbicide weed control required and provide guidance on the length of residual weed control needed to prevent yield loss by weeds. The hypothesis for this research is that lentil would require an extended CPWC with a delayed beginning. It is believed that by delaying weed control, in comparison to conventional lentil herbicide application, the efficiency of weed control in lentil would increase as more of the weed seed bank would have emerged and both the crop and weeds would be too small to compete for resources. Previous research indicated that the CPWC of lentil did not begin until the crop had grown for two to six weeks therefore indicating lentil can withstand some early weed competition under some conditions (Singh et al. 1996;

Mohamed et al. 1997). Furthermore, since lentil is considered an uncompetitive crop it likely requires an extended weed-free period (Zimdahl, 1980).

3.2. Materials and Methods

3.2.1. Experimental location and design

Field experiments were conducted in 2006 and 2007 at the Kernen Crop Research Farm (KCRF) near Saskatoon, SK (lat 52°09’, long 106°33’) and at the BASF Canada Research and Development (BASF) site near Vanscoy, SK (lat 52°01’, long 107°02’). In 2007 another site was added at the Agriculture and Agri-Food Canada (AAFC) Scott Research Farm (lat 52.4° long 108.8°). The KCRF is on a Sutherland series clay soil (Bradwell Dark Brown Chernozem; 26% sand, 34% silt and 40% clay) with a pH of 6.7 in the Moist Mixed Grassland ecoregion (Acton et al. 1998). The BASF site is located on a loam soil (Bradwell Orthic Dark-Brown; 34% sand, 45% silt and 20% clay) with a pH of 6.1 in the Moist Mixed Grassland ecoregion. The AAFC site was located on a loam soil (Dark Brown Chernozem 38% sand, 40% silt and 21% clay) with a pH of 6.0 in the Moist Mixed Grassland ecoregion. The plots were established on wheat stubble at all locations and the site at Vanscoy was cultivated prior to seeding. Glyphosate (450 g ai ha^{-1}) was applied prior to seeding at Scott and Saskatoon.

Seed of CDC Impact, a small red IMI-tolerant lentil, was obtained from the University of Saskatchewan Breeder Seed Division in 2006 and from a local pedigreed seed grower in 2007. The crop was sown with a cone seeder using disk openers with a row spacing of 20 cm. CDC Impact was seeded at 49 kg ha^{-1} for a target population of 120 plants m^{-2}. Nodulator® granular rhizobium inoculum was applied at 7.3 kg ha^{-1} with the seed. A fertilizer blend of 11-52-0 was applied at 20 kg ha^{-1} of actual fertilizer. Plot areas were rolled with a land roller after seeding and before crop emergence at the KCRF and AAFC locations to push any protruding rocks into the soil for ease of harvest. Individual plots were six meters long and two meters wide. Weed species were seeded perpendicular to the crop seed rows immediately before the crop was seeded, to augment the natural weed community. The weed species included: wild oat, green foxtail (*Setaria viridis* (L). Beauv.), wild mustard, wild buckwheat (*Polygonum convolvulus* L.), kochia (*Kochia scoparia* (L.) Schrad.), and redroot pigweed (*Amaranthus retroflexus* L.). Weed seeds were combined and seeded at 50 seeds m^{-2} for each species.

3.2.2. Experimental procedures

A randomized complete block design with four blocks was used at all locations. The experiment consisted of two separate components of the CPWC: the duration of weed interference and the duration of the weed-free period. The first component investigated the duration of weed interference in which weeds were removed at 0 (pre-emergent), 1, 3, 5, 7, 9 and 11 above-ground lentil nodes as well as at physiological maturity (PM). Weed removal was achieved by herbicide application and hand weeding. Imazamox (20 g ai ha^{-1}), imazethapyr / imazamox (30 g ai ha^{-1}) and sethoxydim (500 g ai ha^{-1}) were used for weed control. Merge^{TM} adjuvant was included with these herbicides at a rate of 0.5% v/v. At Saskatoon and Vanscoy herbicides were applied using a two meter, four nozzle, handheld sprayer equipped with Airmix^{TM} 11015 flat fan nozzles calibrated to deliver a volume of 100 L ha^{-1} at 276 kPa with CO_2 as a propellant. At Scott herbicides were applied using a two meter Rogers push-type sprayer with four nozzles equipped with Airmix^{TM} 80015 nozzles calibrated to deliver a volume of 100 L ha^{-1} at 276 kPa with CO_2 as a propellant.

The second component of the CPWC investigated was the duration of the weed-free period required to prevent yield loss. The crop was managed to remain weed-free until the 0 (pre-emergent), 1, 3, 5, 7, 9 and 11 above-ground lentil nodes as well as until PM. After the specified period newly emerged weeds were not controlled. This was achieved by herbicide application and hand weeding. Similar to the above treatments, imazamox (20 g ai ha^{-1}), imazethapyr / imazamox (30 g ai ha^{-1}) and sethoxydim (500 g ai ha^{-1}) were used for weed control. Merge^{TM} adjuvant was included with these herbicides at a rate of 0.5% v/v.

Weed biomass sampling was done at the time of weed removal for the treatments investigating the duration of weed interference and at PM (BBCH=81) (Hess et al. 1997) for the duration of weed-free period treatments. Weed biomass was collected from one meter in from both ends of each plot using 0.25 m^2 quadrants. The weeds were separated according to species and dried at 160°C for two days and then weighed.

Lentil diseases were managed by applying 250 g ai ha^{-1} pyraclostrobin or 2500 g ai ha^{-1} chlorothalonil when lentil was at 50% flower stage. The plots were desiccated using 240 g ai ha^{-1} diquat when the bottom third of the lentil plant had dark brown pods which rattled when shaken

(BBCH= 83) (Hess et al. 1997). The plots were harvested at senescence (BBCH= 97) with a plot harvester. The harvest samples were cleaned using a Carter Day Dockage Tester^{TM} and further cleaned manually when required to remove weed seeds. The samples were weighed to determine yield when air dry.

3.2.3. Statistical analysis

Analysis of variance using mixed model procedures in SAS (SAS Institute Inc., version 9.1.2, 2003) was initially performed to test the significance of the duration of weed interference and the duration of the weed-free period on weed biomass and lentil yield. Site year, block within site year and treatment by site year were considered as random effects and the duration of weed interference / duration of the weed-free period (treatments) as fixed effects. There was a significant site year by treatment effect for both weed biomass and lentil yield therefore the data were further analyzed within site years. Analysis of variance was then conducted for weed biomass and lentil yield within site years with block included as a random effect and the duration of weed interference and the duration of the weed-free period as fixed effects.

Lentil yield and weed biomass treatment averages within site year were further analyzed using logistic and Gompertz regression procedures as described by Hall et al. (1992). Weed biomass and lentil yield were regressed against the lentil developmental stages (nodes) for the weedy (duration of weed interference) or weed-free (duration of the weed-free period) treatments using logistic and Gompertz equations, respectively.

The logistic equation from Hall et al. (1992) was modified to best describe the weed biomass and lentil yield response to the increasing duration of weed intereference (Equations 3.1 and 3.2). Weed biomass response to the duration of weed interference was modelled using a modified three parameter logistic equation (Knezevic et al. 2007) as follows:

$$WB = \frac{D}{1 + \exp(-K(S - T))} \qquad [3.1]$$

where WB is weed biomass expressed in g m^{-2}, D is the maximum biomass in the absence of weed control or the upper asymptote, K is the rate of increase of weed biomass as observed in the absence of weed control, T is the lentil stage at which weed biomass was 50% of the maximum biomass (D) and S is the stage of lentil development.

Only the yield results from the three site years in 2007 could be used to determine the effect of the duration of weed interference on lentil yield as the 2006 treatments were not kept weed-free after the initial weed removal. The lentil yield response was modelled using a modified four parameter logistic equation as follows:

$$Y = C + \frac{D - C}{1 + \exp[K(T - S)]} \qquad [3.2]$$

where Y is yield expressed in kg ha^{-1}, C is the minimum yield in the absence of weed control or the lower asymptote, D is the maximum yield under weed-free conditions or the upper asymptote, K is the rate of decrease of lentil yield by delaying weed control, T is the developmental stage at which yield was 50% of the maximum yield and S is the stage of lentil development.

The Gompertz equation from Hall et al. (1992) was further modified to best describe the weed biomass and lentil yield response to the increasing duration of the weed-free period (Equations 3.3 and 3.4) (Forcella et al. 2000). Weed biomass response to the duration of the weed-free period was modelled using a modified 3 parameter equation as follows:

$$WB = D + (-D)\exp(-B(\exp(-KS)) \qquad [3.3]$$

where WB is weed biomass expressed in g m^{-2}, D is the maximum biomass in the absence of weed control or the upper asymptote, B is a constant that defines the lag time prior to the decrease in weed biomass, K is the rate of decrease of weed biomass as observed by an increasing weed-free periods and S is weed-free period expressed in lentil nodes.

The lentil yield response was modelled using a modified four parameter logistic equation as follows:

$$Y = C + (D - C)\exp(-B\exp(-KS)) \qquad [3.4]$$

where Y is yield expressed in kg ha^{-1}, C is the minimum yield or the lower asymptote, D is the maximum yield or the upper asymptote, B is a constant that defines the lag time prior to the increase in yield, K is the rate of lentil yield increase as observed by an increasing weed-free period and S is weed-free period expressed in lentil nodes.

A quantified crop stage (nodes) was required for regression analysis to regress the lentil yield response until physiological maturity (PM). The number of lentil nodes at PM was not determined because lentil had ceased producing nodes after entering the reproductive stage. Therefore, as a proxy, the equivalent time to PM in nodes was estimated by measuring the growing degree days (GDD) required for the development of lentil nodes earlier in the season and dividing by the GDD at PM. Thus the equivalent number of lentil nodes at PM was 23 and this number was used for regression analysis.

All logistic and Gompertz equations were modelled using the DRC package in the statisitcal analysis package R (R Development Core Team, 2008). The site years could not be combined because there was a site year by treatment interaction (Table 3.1) and each site year was analyzed separately. To determine whether there was similar weed biomass or lentil yield responses to the duration of weed interference or the duration of the weed-free period, common C, D, K, B and T values were compared for the appropriate equations. Parameters in equations 3.1, 3.2, 3.3 and 3.4 were compared using common values. Common values for the parameters were used in the equations when the values were significant ($P<0.05$). If the common values were not significant ($P>0.05$) then individual values were used for each site year.

3.3. Results and Discussion

Weed biomass and lentil yield response to the duration of weed interference and the duration of the weed-free period differed among the site years (Table 3.1). The variation in yield and weed biomass was presumably a function of the environmental conditions at each respective site year (Table 3.2).

Table 3.1 Analysis of variance for the effect of the duration of weed interference and the duration of weed-free period on weed biomass, lentil yield and the effect on each site year (Pr>*F*).

	Weed Biomass		Crop Yield	
	Duration of Weed Interference	*Duration of Weed-Free Period*	*Duration of Weed Interference*	*Duration of Weed-Free Period*
Site Year	0.2920	0.1474	0.1649	0.0896
Block (Site Year)	0.3831	0.0951	0.2575	0.0259
Site Year * Treatment	0.0249	0.0088	0.0111	0.0007
Treatment	0.0005	<0.0001	0.0054	<0.0001
Treatment within Site Year				
Saskatoon, 2006	-	<0.0001	-	<0.0001
Vanscoy, 2006	-	<0.0001	-	<0.0001
Saskatoon, 2007	<0.0001	0.0002	<0.0001	<0.0001
Vanscoy, 2007	<0.0001	0.0152	<0.0001	<0.0001
Scott, 2007	<0.0001	<0.0001	0.0013	<0.0001

Growing conditions at all site years were good overall with near normal temperatures. Precipitation, however, did not generally follow the 30 year trend (Table 3.2). In both years, June precipitation at all sites was approximately 60% higher than the 30 year average. The July precipitation was much lower for both years at all sites. In 2006, Vanscoy received approximately 80% less than the overall average precipitation in August whereas the Saskatoon site was near normal. August 2007 precipitation at Saskatoon was much higher than the 30 yearaverage however precipitation at Vanscoy and Scott was near normal. Therefore it is likely that the variation in the precipitation among the site years contributed to the variation in lentil yield and weed biomass to the treatments.

Table 3.2 Monthly rainfall (mm) and the mean daily temperature (°C) for Vanscoy, Saskatoon and Scott from May until August in 2006 and 2007 and the long-term (30 year) average of each location.

Location	Month	Rainfall			Temperature		
		2006	2007	30 year average†	2006	2007	30 year average†
		mm			C		
Vanscoy	May	45	55	47	12.2	11.6	11.5
	June	100	113	61	16.3	16.4	16.0
	July	22	24	60	19.8	23.1	18.2
	August	7	49	39	18.0	17.1	17.3
	Total	174	241	207	-	-	-
Saskatoon	May	58	41	47	11.0	10.7	11.5
	June	111	100	61	16.2	14.8	16.0
	July	46	31	60	20.0	20.9	18.2
	August	35	119	39	18.0	15.4	17.3
	Total	250	291	207	-	-	-
Scott	May	-	79	35	-	10.4	10.9
	June	-	103	63	-	14.0	15.2
	July	-	14	71	-	20.4	17.0
	August	-	36	43	-	14.7	16.3
	Total	-	232	212	-	-	-

†30 year averages (1971- 2000) obtained from Environment Canada (2004).

Growing conditions in 2006 and 2007 facilitated good weed emergence and growth at all sites (Table 3.3). Site years differed greatly in weed shoot density and biomass accumulation. For example, the overall highest weed shoot density occurred at Saskatoon in 2006, while in 2007 the site at Scott had approximately 55% to 70% lower density than the other site years. Furthermore, the weed biomass was lowest for Saskatoon in 2007 and Scott in 2007 was 70% greater. The large variation in weed shoot density and biomass production between the site years was presumably caused by the differences in environmental conditions. This likely caused the site year by treatment interactions (Table 3.1).

Table 3.3. Average weed density and biomass at five site-years in Saskatchewan measured from the weedy control plot at lentil physiological maturity (BBCH =81).

Location	Year	Weed‡	Shoot Density	Shoot Biomass
			shoots m^{-2}	g m^{-2}
Saskatoon	2006	wild oat	135	140
		green foxtail	9.2	0.7
		wild buckwheat	19	0.9
		red root pigweed	34	5.8
		wild mustard	24	300
		Total	*225*	*450*
	2007	wild oat	78	124
		green foxtail	110	18
		wild mustard	2.0	100
		stinkweed	16	24
		wild buckwheat	6.0	2.7
		lambs quarters	1.4	6.4
		Total	*210*	*280*
Vanscoy	2006	wild oat	120	370
		green foxtail	5.0	3.4
		wheat	11	12
		Japanese brome	8.3	2.8
		wild buckwheat	4.8	14
		red root pigweed	4.0	6.4
		prostrate knotweed	2.2	2.4
		lambs quarters	1.0	3.9
		Total	*160*	*420*
	2007	wild oat	89	400
		green foxtail	4.6	3.9
		Japanese brome	30	20
		wheat	7.2	17
		lambs quarters	10	90
		red root pigweed	2.7	3.6
		wild buckwheat	6.0	8.0
		Total	*150*	*540*
Scott	2007	wild oat	24	324
		green foxtail	5.3	7.0
		wild mustard	16	637
		red root pigweed	20	4.8
		wild buckwheat	2.1	0.9
		lambs quarters	2.3	5.3
		Total	*70*	*980*

‡ Weed species: wild oat (*Avena fatua* L.), green foxtail (*Setaria viridis* (L.) Beauv.), wheat (*Triticum aestivum* L.), Japanese brome (*Bromus japanicua* L.), red rooted pigweed (*Amaranth retroflexus* L.), wild buckwheat (*Polygonum convolvulous* L.), lamb's quarters (*Chenopodium album* L.), stinkweed (*Thalapsis arvense* L.), prostrate knotweed (*P. aviculare* L.) wild mustard (*Sinapsis arvensis* L.)

3.3.1. Duration of weed interference

Weed Biomass

There was a significant weed biomass response to increasing durations of weed interference (Table 3.1). Weed biomass measured at the time of weed control increased as the duration of weed interference increased (Figure 3.1). The relationship was well described by the logistic regression with common parameters fitted for K and T (Table 3.4).

Weed biomass response to the duration of weed interference was generally similar among the site years (Figure 3.1). Weeds emerged at approximately the same time as the crop at all site years (data not shown). There was little weed biomass when weed removal took place at the one, three and five lentil node stages. Weed biomass began to increase when weed control was delayed until the seven node stage. Starting at the seven node stage, delayed weed removal resulted in nearly linear weed biomass accumulation until the 11 node stage where weed removal ceased. Presumably weed growth and biomass accumulation plateaued after the 11 node stage since both the crop and weeds were nearing the reproductive stages where vegetative growth would have slowed.

Weed biomass response to delayed weed control resulted in common parameters describing the curve for each site year; however, each site year required a unique value for the upper asymptote (D) (Figure 3.1; Table 3.4). The upper asymptote describes maximum weed biomass accumulation and differences were likely due to environmental conditions (Table 3.2) and weed species composition (Table 3.3). Common K and T values indicated that the environmental effect on these parameters was negligible. Therefore, the effect of weed control timing on weed biomass accumulation is constant along with the relative rate of biomass accumulation.

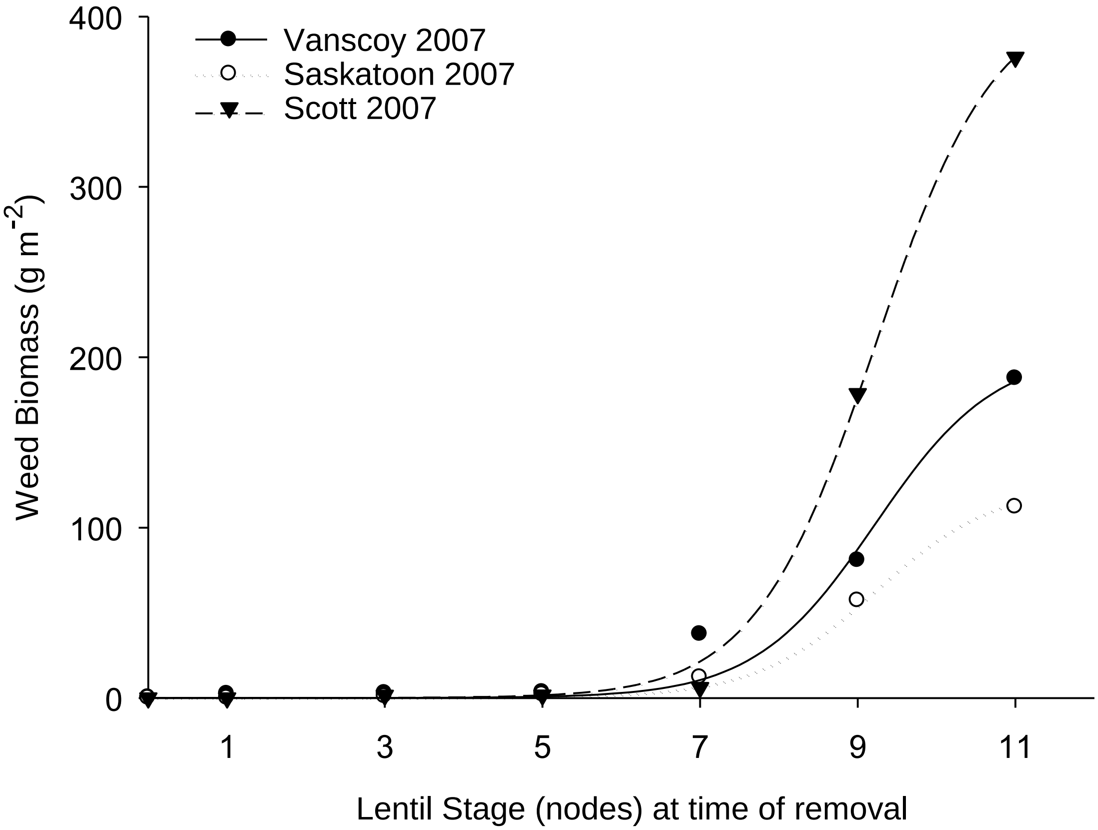

Figure 3.1 Weed biomass response to increasing duration of weed interference for Scott, Saskatoon and Vanscoy in 2007. Points represent observed mean values whereas the lines represent the fitted curves of the three-parameter logistic equation. Parameter values for the logistic model are listed in Table 3.4.

Table 3.4 Parameter estimates (standard error) by site year for the three-parameter logistic model characterizing the weed biomass response to the duration of weed interference.

		Parameter Estimates		
Site	Year	D g m^{-2}	K g m^{-2} nodes^{-1}	T Nodes
Saskatoon	2007	130 (10)	-1.3 (0.2)	9.2 (0.1)
Vanscoy	2007	200 (13)	-1.3 (0.2)	9.2 (0.1)
Scott	2007	410 (21)	-1.3 (0.2)	9.2 (0.1)

Lentil Yield

Lentil yield response to increasing durations of weed interference was significant (Table 3.1). Lentil yield decreased as weed removal was delayed (Figure 3.2). There was no yield penalty associated with weed removal at the one, three or five node stage. All three weed removal timings were comparable to the weed-free treatment (ie. zero nodes). With the exception of Vanscoy in 2007, delayed weed removal past the five node stage generally resulted in reduced lentil yield in comparison to the weed-free treatment. When weed removal was delayed until the seven node stage there was an linear decrease in yield until the 11 node stage when the yield reached a minimum and was comparable to season long weed growth (ie. until PM).

Lentil yield response to the duration of weed interference was adequately described by the four parameter logistic equation (Equation 3.2; Table 3.5). A common rate of response (K) and the time at which 50% of the maximum yield was achieved (T) were significant indicating the lack of environmental effect on the response to the duration of weed interference. Separate upper (D) and lower (C) asymptotes were needed for each environment. The differences between locations were likely a result of differential weed competition at each location and environmental differences (Tables 3.2 and 3.3). Sites with increased weed biomass also had the largest decrease in lentil yield (Figures 3.1 and 3.2). For example, in 2007 the greatest weed biomass and the greatest lentil yield reduction occurred at Scott (Figures 3.1 and 3.2). This relationship is further confirmed by the low weed biomass at Saskatoon in 2007 and the relatively small reduction in lentil yield.

Lentil yield at Vanscoy in 2007 (Figure 3.2) shows little change over time and did not respond to the duration of weed interference as much as at Scott and Saskatoon in 2007. However, the common relative rate of yield loss (K) is significant and is proportional to the other locations (Table 3.5). This indicates that the absolute yield loss may differ between sites but the rate at which the relative yield loss occurs is constant.

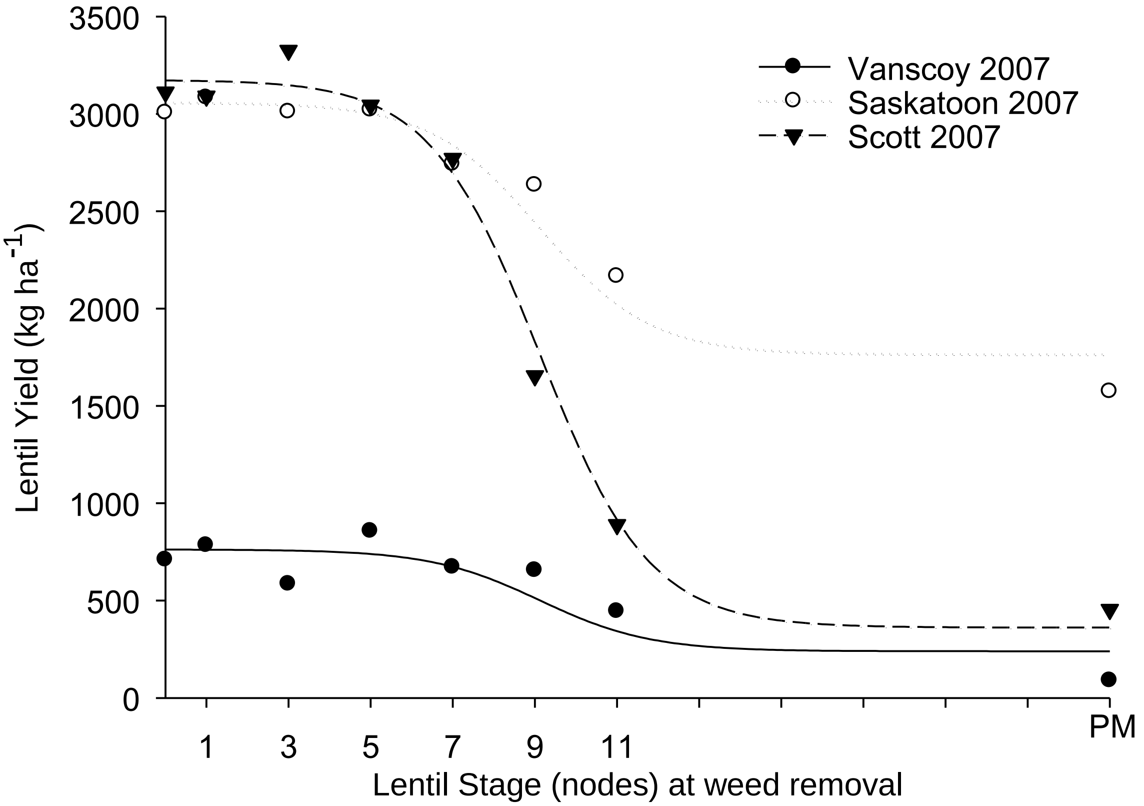

Figure 3.2 Yield response to the duration of weed interference for Scott, Saskatoon and Vanscoy in 2007. Points represent observed mean values whereas the lines represent the fitted curves of the modified four parameter logistic equation. Parameter values for the logistic equation are listed in Table 3.5.

Table 3.5 Parameter estimates (standard error) by site year for the four-par**ameter logistic model characterizing the lentil yield response to increasing durations of weed interferenc**e.

		Parameter Estimates			
Site	Year	C kg ha^{-1}	D kg ha^{-1}	K kg ha^{-1} nodes^{-1}	T nodes
Saskatoon	2007	1800 (110)	3100 (65)	0.75 (0.11)	9.1 (0.25)
Vanscoy	2007	240 (100)	760 (63)	0.75 (0.11)	9.1 (0.25)
Scott	2007	360 (130)	3200 (74)	0.75 (0.11)	9.1 (0.25)

A common rate of response (*K*) was significant for lentil yield loss and weed biomass accumulation among all site years (Tables 3.4 and 3.5). Due to the similar responses between environments, it can be concluded that weed biomass has a similar effect on yield reduction regardless of amount of weed biomass accumulated or yield potential. Therefore, it is no coincidence that unacceptable yield losses occured when weeds grew after the five to seven node stage (Figure 3.2), which coincided with the time when the weeds began to accumulate significant amounts of biomass (Figure 3.1). At the time when significant weed biomass accumulation began, both the weeds and crop were competing for resources which resulted in lentil yield loss.

3.3.2. Duration of the weed-free period

Weed Biomass

Weed biomass decreased significantly as the duration of the weed-free period increased (Figure 3.3; Table 3.1). Overall, weed biomass at harvest was greatest when weeds emerged early in lentil development (Figure 3.3). For example, weeds emerging at the one node stage produced biomass comparable to weeds that emerged at the same time as the crop (ie. zero node). There was a near linear decrease in weed biomass for most sites beginning at the three node stage and continuing until the seven node stage. The curves reached a minimum at the nine to11 node stage.

The Gompertz regression described the effect of the duration of the weed-free period on weed biomass and a common value for the rate of weed biomass accumulation (*K*) was significant (Table 3.6). A common lower (*D*) asymptote and lag period (*B*) were not significant which was likely due to differences in environmental conditions (Table 3.2 and 3.3).

There was a drastic decrease in weed biomass when the weed-free period lasted until the one node stage for Vanscoy in 2006 and 2007 and Saskatoon in 2006 (Figure 3.3). There was a weed biomass decrease at Scott in 2007 when the weed free period lasted until the three node stage. Lastly, Saskatoon in 2007 required a lengthy weed-free period before there was a decrease in weed biomass. The decrease in weed biomass was nearly linear after the one node stage until the six to seven node stage for Vanscoy in 2006 and 2007 as well as at Saskatoon in 2006. This is reflected in the equation parameters where each lag period (*B*) was between the six to seven

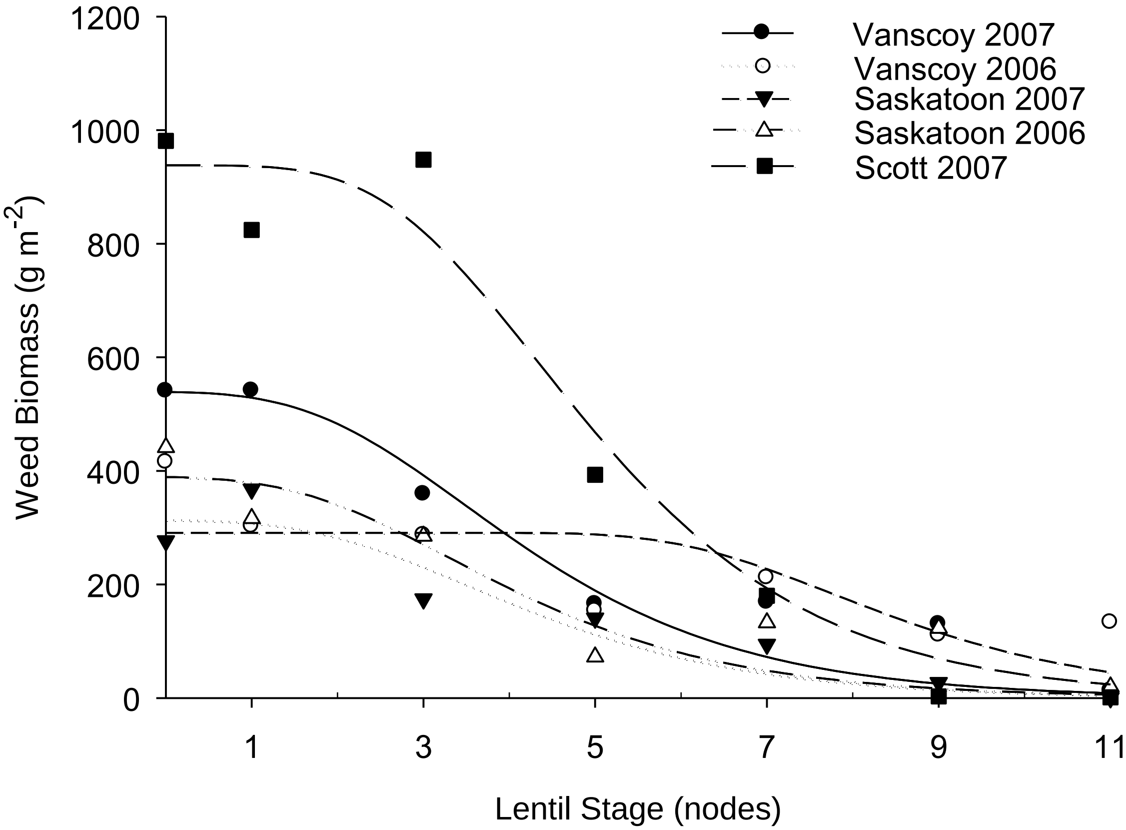

Figure 3.3 Weed biomass response to the duration of the weed-free period for Scott in 2007, Saskatoon in 2006 and 2007, as well as Vanscoy in 2006 and 2007. The points represent the observed values whereas the lines represent the fitted curves for the modified 3 parameter Gompertz equation. Parameter values are listed in Table 3.6.

Table 3.6 Parameter estimates (standard error) by site year for the three-parameter Gompertz model characterizing the weed biomass response to the duration of the weed-free period.

Site	Year	Parameter Estimates		
		D	K	B
		g m^{-2}	g m^{-2} nodes^{-1}	Nodes
Saskatoon	2006	390 (69)	0.55 (0.13)	6.2 (5.2)
	2007	290 (50)	0.55 (0.13)	71 (130)
Vanscoy	2006	310 (61)	0.55 (0.13)	6.9 (5.6)
	2007	540 (63)	0.55 (0.13)	6.8 (4.2)
Scott	2007	940 (53)	0.55 (0.13)	10 (6.9)

node stages (Table 3.6). The weed biomass response for these sites reached a minimum between the nine and 11 node stage, or presumably the ten node stage. A large response to the duration of the weed-free period occurred at Scott in 2007 and weed biomass did not reach a minimum until the 11 node stage. There was a small and delayed response (*B*) to the increasing duration of the weed-free period at Saskatoon in 2007. The weeds required an extended weed-free period to reach a minimum biomass. According to the lag period estimates (Table 3.6), Saskatoon in 2007 required 71 nodes before the weed biomass levelled off, which is impossible. However, such a high and biologically irrelevant value indicates that the model was not able to fit a realistic value. The weed biomass values for Saskatoon in 2007 exhibited great variability resulting in an inflated prediction for the lag period (Figure 3.3).

Weed biomass rate of response to the increasing duration of the weed-free period was common among all site years (Table 3.6). This was similar to the weed biomass rate of response to the duration of weed interference (Table 3.4). The common rate of response among both measurements further confirms that the weed biomass rate of response is relative to the increasing weed-free period / duration of weed interference and irrespective of environment (Tables 3.2 and 3.3) and biomass accumulation potential at each site year.

Lentil Yield

The duration of the weed-free period had a significant effect on lentil yield (Table 3.1). Lentil yield increased with an extended weed-free period (Figure 3.4). The average lentil yield varied among the five site years. The yield of weed-free treatments ranged from 700 to 3200 kg ha^{-1} at Vanscoy in 2007 and Scott in 2007, respectively. Conversely treatments that were weedy for the entire season (ie. zero node) ranged from 100 to 1500 kg ha^{-1} at Vanscoy in 2007 and Saskatoon in 2007, respectively.

The Gompertz equation adequatley described the relationship between lentil yield and increasing weed-free periods. The equation parameters (Table 3.7) show a common rate of yield response (*K*) for all site years. A common lower asymptote, upper asymptote and lag period were not significant and separate values were required.

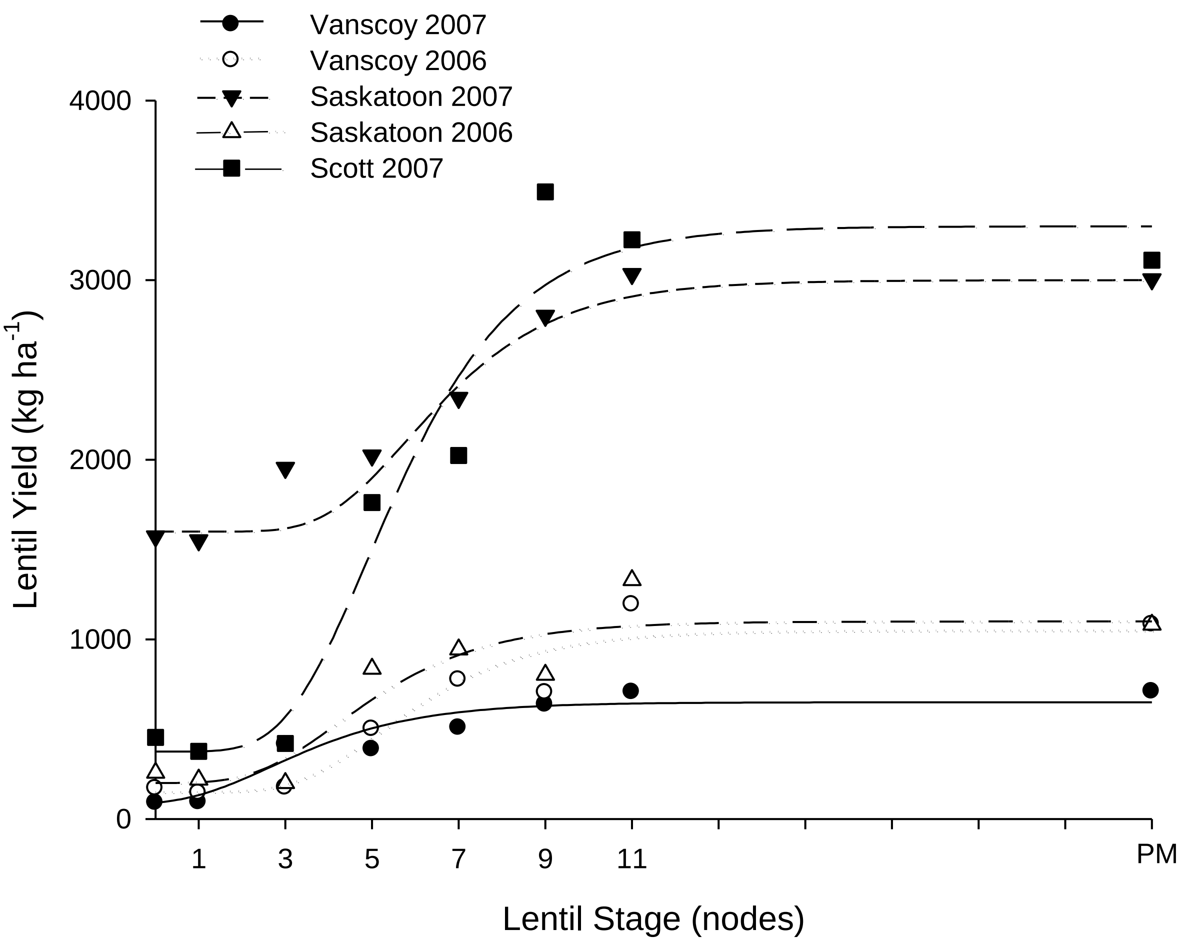

Figure 3.4 Lentil yield (kg ha^{-1}) response to the duration of the weed-free period for Vanscoy in 2006 and 2007, Saskatoon in 2006 and 2007 as well as Scott in 2007. Points represent observed mean values whereas the lines represent the fitted curves of the modified Gompertz equation. Table 3.7 lists the parameter estimates for the modified Gompertz equation.

Table 3.7 Parameter estimates (standard error) by site year for the four-parameter Gompertz model characterizing the relationship between lentil yield and the duration of the weed-free period.

Site	Year	Parameter Estimates			
		C	D	K	B
		kg ha^{-1}	kg ha^{-1}	kg ha^{-1} nodes^{-1}	Nodes
Saskatoon	2006	210 (140)	1100 (120)	0.52 (0.09)	9.1 (5.9)
	2007	1700 (130)	3000 (150)	0.52 (0.09)	21 (18)
Vanscoy	2006	160 (130)	1100 (140)	0.52 (0.09)	16 (13)
	2007	79 (210)	650 (120)	0.52 (0.09)	4.4 (5.9)
Scott	2007	380 (140)	3300 (150)	0.52 (0.09)	13 (6.4)

Generally, the longer the duration of the weed-free period the higher the lentil yield (Figure 3.4). Lentil yield increased with a weed-free period lasting three nodes or longer for all site years. Weed-free periods lasting less than three nodes resulted in yield similar to the weedy check (ie. zero node). However, the weed-free period required to reach maximum yield varied for each site. There was a linear increase in lentil yield from the three to the nine node stage at Saskatoon and Scott in 2007 and after the nine stage maximum lentil yield was reached. There was a linear yield increase at Vanscoy and Saskatoon in 2006 also starting at the three node stage but this continued only until seven nodes. An unexplained yield decrease occurred when the duration of the weed-free period was until nine nodes at both locations in 2006 (Figure 3.4). After the nine node stage the yield reached a maximum. There was a linear increase in lentil yield from the one to the five node stage at Vanscoy in 2007 and maximum yield was reached between the seven and nine node stage. Therefore, the weed-free period required to prevent yield losses was between the seven to 11 node stages, but largely depended on the yield potential. Interestingly, the weed-free period required to prevent yield loss typically coincided with canopy closure.

The relationship between lentil yield and increasing weed-free periods was similar among site years. The common lentil yield rate of response (*K*) (Table 3.7) to increasing weed-free periods indicates that the yield response to the weed-free period among site years was proportionally the same regardless of the yield potential. Biologically irrelevant lag periods of 16 and 21 nodes resulted for Vanscoy in 2006 and Saskatoon in 2007, respectively. This was likely due to the variability within the yield results or perhaps due to the relatively small yield difference between the lower and upper asymptote and the extended time required for the model curve to predict maximum yield.

Lentil yield and weed biomass displayed opposing responses to the duration of the weed-free period (Figures 3.3 and 3.4). The longer the weed-free period, the lower the weed biomass and the higher lentil yield. Weed biomass was reduced when the weed-free period lasted longer than the three node stage for all site years except Saskatoon in 2007 (Figure 3.4). Lentil yield increased when the weed-free period lasted longer than three nodes, except for Vanscoy in 2007. Furthermore, weed-free periods lasting until 11 nodes resulted in relatively little weed biomass and maximum yield.

3.4. Critical Period of Weed Control for Lentil

The critical period of weed control (CPWC) was realized for lentil by combining the yield responses to the duration of weed interference and the duration of the weed-free period. The CPWC was determined for: Scott, Saskatoon and Vanscoy in 2007. The critical periods of weed control (CPWC) were determined based on five percent acceptable yield loss. The CPWC for Vanscoy in 2007 began at the five node stage and continued until the eight node stage (Figure 3.5). At Saskatoon in 2007 the CPWC was from the six node to ten node stage. Lastly, the CPWC at Scott in 2007 was from the five node to ten node stage. It was observed that the end of the CPWC often coincided with lentil canopy closure. Therefore, the CPWC for lentil generally begins at the five node stage and ends at the ten node stage. The defined CPWC encompasses all site years and weed growth outside this period should not affect yield.

The critical period of weed control (CPWC) has previously been studied for lentil in Sudan (Mohamed et al. 1997) and Jordan (Singh et al. 1996). Similar to our research, the CPWC began after crop emergence but still early within the growing season. Therefore, early season weed control is most important in preventing yield loss. However, due to environmental differences between Sudan, Jordan and western Canada very few other comparisons can be made. Therefore, this research is the first to define the CPWC for lentil in western Canada.

3.5. Conclusion

The CPWC in lentil is between the five and ten node stage but differed slightly between locations (Figure 3.5). The beginning and end of the CPWC differed depending on the yield potential of each site year and the extent of weed competition. Cultivation or herbicide application prior to seeding did not seem to have an effect on the CPWC. Generally, the CPWC began at the onset of significant weed biomass accumulation. Therefore, to prevent yield loss, weeds should be controlled at the onset of significant weed biomass accumulation. In situations where high weed populations and delays in weed control could cause large yield losses, weeds should be removed with herbicide application at the five node stage. The importance of weed removal at this time is illustrated by the results at Scott in 2007. When weed control was delayed until the seven node stage there was a 16% yield decrease versus a 4% decrease when weeds were removed at the five node stage. In situations where weed germination and growth are

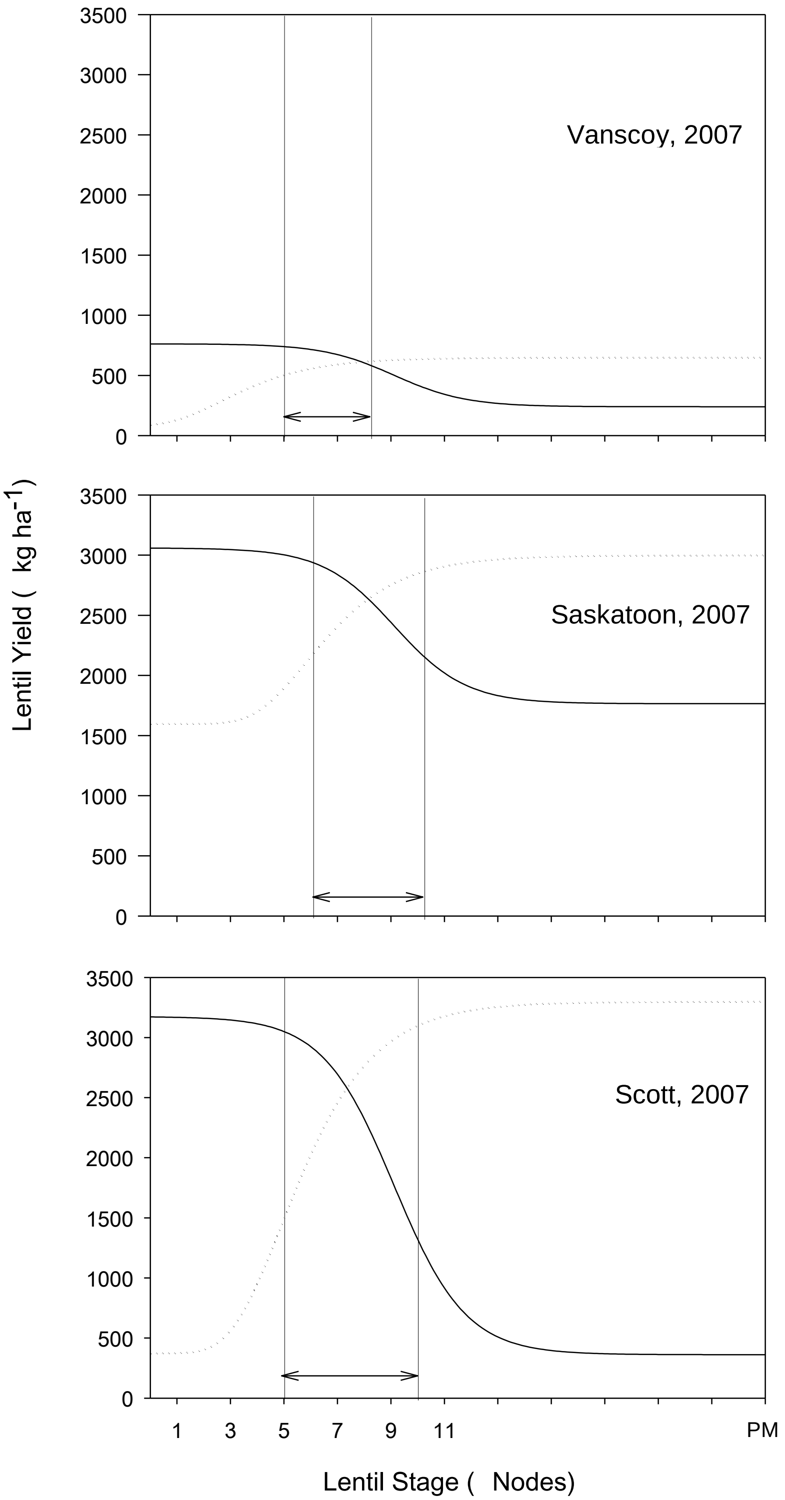

Figure 3.5 Duration of weed interference (solid line) and the duration of the weed-free period (dotted line) for Vanscoy, Saskatoon and Scott in 2007. The CPWC for each site year is between the arrows.

relatively low, weeds should be removed with herbicide application at the six node stage as represented by Saskatoon and Vanscoy in 2007. The end of the CPWC was observed to often coincide with lentil canopy closure which likely shaded the soil and restricted subsequent weed cohorts (Norsworthy and Oliveira, 2004).

The determination of the CPWC for lentil provides evidence that there is a potential for a residual herbicide to be used at the five to six node stages of lentil to control weeds until the ten node stage, or throughout the CPWC, to prevent yield losses. The residual effect of the IMI herbicides is not known in the context of the CPWC. Therefore, further research is needed to determine whether a single application of an IMI herbicide is sufficient to control weeds within the CPWC or whether additional applications are required.

4.0 Influence of herbicide and herbicide application timing on weed biomass and imidazolinone tolerant lentil yield

4.1. Introduction

Weeds are a limiting factor in lentil production and cause substantial yield loss (Tepe et al. 2004). Weeds compete with lentil for light, moisture and nutrients. Swanton et al. (1993) estimated weeds caused an average of 14% yield loss in lentil annually in Saskatchewan, the highest yield reduction due to weeds of all the major crops grown in western Canada. Yield losses up to 100% have also been documented (Erman et al. 2004). Blackshaw et al. (2002) ranked lentil as the least competitive crop grown in western Canada. Its poor competitive ability is a function of the plants reduced early vigour, short stature, slow rate of development, sparse canopy and late canopy closure (Blackshaw et al. 2002).

Weed control in lentil production is difficult as there are few herbicide options available for control of many weeds. Registered post-emergent (POST) herbicides include clethodim and sethoxydim as well as metribuzin (SMA, 2008). There are many graminicides for control of grass weeds but only one herbicide for POST broadleaved weed control (metribuzin). Furthermore, there are no graminicides registered in combination with metribuzin for control of both grass and broadleaved weeds in a single application.

Metribuzin is not an ideal herbicide for use in lentil. Metribuzin has been documented to cause injury to crops including soybean which resulted in leaf drop, leaf burn, chlorosis and subsequent yield loss (Malik and Townley-Smith, 1990). These symptoms have also been observed in lentil (Friesen and Wall, 1986; SPG, 2000). Metribuzin provides only variable control of many of the economically important weeds in lentil production including stinkweed (*Thalapsi arvensis* L.), wild mustard (*Sinapsis arvensis* L.) (Cessna, 1997) and lambs quarters (*Chenopodium album* L.) (SMA, 2008) but fails to control wild buckwheat (*Polygonum convolvulous* L.). Furthermore, the application period of metribuzin is restricted as it can only be applied until the four node stage to ensure crop safety. As a result of metribuzin's poor broadleaved weed control and phytotoxic effects, many producers have resorted to the unregistered use of a reduced rate of imazethapyr. However, imazethapyr is not registered in the brown and dark brown soil zones (SMA, 2008) due to carry over issues to crops seeded one year after application (Curran et al. 1991; Blackshaw, 1998). A large proportion of lentil production is in these soil zones (SPG, 2000).

To address poor broadleaved weed control in lentil, herbicide tolerant (HT) lentil varieties with imidazolinone (IMI) tolerance were developed at the University of Saskatchewan, Crop Development Center (CDC) (Chant, 2004). The IMI herbicides control a broad range of grass and broadleaved weeds (Klingaman et al. 1992; Alister and Kogan, 2005; Shaner and Hornford, 2005; Ball et al. 2003) and are commonly used in other field crops in Saskatchewan including field pea (*Pisum sativum*, L.), forage legumes, Clearfield® (CL) wheat (*Triticum aestivum* L.), CL canola (*Brassica rapa* L.) and CL corn (*Zea mays* L.) (Tan et al. 2005). More herbicide options are available for IMI lentil and these herbicides have increased efficacy in comparison to the conventional lentil herbicides. Furthermore, the IMI herbicide application period is longer and the herbicides can be safely applied until the 11 node without injuring the crop (Chant, 2004).

The critical period of weed control (CPWC) concept determines the period in which a crop must be kept weed-free to prevent significant yield losses (Knezevic et al. 2003). The CPWC of lentil has been determined to be from the five node to 10 node stage in western Canada (Chapter 3). However, metribuzin must be applied prior to the four node stage (SMA, 2008) and is usually applied earlier. In contrast, IMI herbicides can be applied much later (Chant, 2004) which can correspond to the CPWC of lentil. Furthermore, IMI herbicides are soil active and can provide extended control of late emerging weeds (Alister and Kogan, 2005) possibly extending weed control throughout the CPWC. Imazethapyr persists in the soil longer than imazamox (Blackshaw, 1998; Ball et al. 2003; Shaner and Hornford, 2005).

This chapter investigates the effect of imazamox, imazethapyr / imazamox and metribuzin followed by sethoxydim on weed control and lentil yield applied at the two (early) and six (late) node stages of lentil. These herbicides provide varying levels of weed efficacy, crop tolerance and residual weed control. Metribuzin can provide variable broadleaved weed control (Malik and Townley-Smith, 1990), does not control grass weeds (SMA, 2008) and does not provide residual weed control at the rates used in lentil (Bouchard et al. 1982). Sethoxydim was included in the study for control of grass weeds in the metribuzin treatments. Imazamox and imazethapyr / imazamox control most of the economically important weeds in lentil and there are no crop tolerance issues in IMI-tolerant lentil (SMA, 2008; Chant, 2004). Imazamox provides low levels of residual weed control and provides increased grass weed control (Blackshaw, 1998; Ball et al. 2003; Shaner and Hornford, 2005). In comparison, imazethapyr / imazamox provides some residual weed control and has increased broadleaf weed control (SMA, 2008). The initial hypothesis for this research was that imazethapyr / imazamox applied early POST would result in the lowest weed biomass and highest lentil yield. This hypothesis was based on the poor competitive ability of lentil with weeds, imazethapyr / imazamox's extended residual weed control and the traditional herbicide application timing in conventional lentil production. However, the CPWC for lentil was determined to be from the five to 10 node stage (Chapter 3) and the hypothesis was revised. Therefore, it is hypothesized that the application of a residual broadleaved herbicide at the late POST application (approximate beginning of the CPWC) will maximize lentil yield by reducing weed biomass. The objective of this study was to validate the CPWC concept by testing application timings of herbicides differing in efficacy and residual control.

4.2. Materials and Methods

4.2.1. Experimental design and location

Field experiments were conducted in 2006 and 2007 at the Kernen Crop Research Farm (KCRF) near Saskatoon, SK (lat 52°09', long 106°33') and at the BASF Canada Research and Development site near Vanscoy, SK (lat 52°01, long 107°02). KCRF is located on a Sutherland series clay soil (Bradwell Dark Brown Chernozem; 26% sand, 34% silt and 40% clay) with a pH of 6.7 in the Moist Mixed Grassland ecoregion (Acton et al. 1998). The BASF site is located on a loam profile (Bradwell Orthic Dark-Brown; 34% sand, 45% silt and 20% clay) with a pH of 6.1 in the Moist Mixed Grassland ecoregion. The plots were established on wheat stubble at both locations and the plots at Vanscoy were cultivated prior to seeding. The plot area at Saskatoon was rolled after seeding and before crop emergence to push any protruding rocks into the soil for ease of harvest.

4.2.2. Experimental procedure

The experiment was conducted as a factorial randomized complete block design with herbicide and herbicide application timing as the main effects. The herbicide treatments included imazamox (20 g ai ha^{-1}), imazethapyr / imazamox (30 g ai ha^{-1}), and metribuzin (206 g ai ha^{-1}) supplemented with sethoxydim (500 g ai ha^{-1}) applied five to seven days after metribuzin for grass weed control. Merge^{TM} adjuvant was added to imazamox, imazethapyr / imazamox and sethoxydim at a rate of 0.5% v/v. Sethoxydim was applied after the metribuzin treatments to avoid antagonism of grass weeds (SMA, 2008; Kirkland et al. 1989). The herbicides were applied to lentil early (two above ground nodes) and late (six above ground nodes) using a two meter wide, four nozzle, handheld sprayer equipped with Airmix^{TM} 110-015 flat fan nozzles. The sprayer was calibrated to deliver a volume of 100 L ha^{-1} at 275 kPa for imazamox, imazethapyr / imazamox and sethoxydim and 173 L ha^{-1} at 275 kPa for metribuzin. The seeding and herbicide application dates as well as lentil and weeds stages at application are listed in Table 4.1.

Plant emergence counts were conducted when lentil was at approximately the two node stage. Weed population density and crop density were measured using two 0.25 m^2 quadrants which included three rows of lentil. Measurements were approximately one meter in from either end of the plots. In 2006, one quadrant was permanently marked for subsequent weed emergence counts and in 2007 there were two permanent quadrants. After the initial herbicide applications all newly emerging weeds were counted and marked with a paperclip to evaluate the length of residual control of the herbicides. The weed counts were carried out at seven to ten day intervals throughout the growing season.

Crop and weed biomass sampling was done at lentil physiological maturity (BBCH= 81) (Hess et al. 1997). Crop and weed biomass was collected from within the permanent quadrants and in 2006 an additional quadrant was sampled. The crop and weeds were separated according to species, dried at 160°C for 48 hours and weighed.

Lentil diseases were managed by applying pyraclostrobin (250 g ai ha^{-1}) when lentil was at the 50% flower stage. The plots were desiccated using diquat (240 g ai L^{-1} ha^{-1}) when the bottom third of the lentil plants had dark brown pods which rattled when shaken (BBCH= 83) (Hess et al. 1997). The plots were harvested at senescence (BBCH=97) with a plot harvester.

Table 4.1 List of seeding and spraying dates as well as the corresponding lentil and weed staging at two locations across central Saskatchewan in 2006 and 2007.

	Saskatoon, 2006	Vanscoy, 2006	Saskatoon, 2007	Vanscoy, 2007
Seeding Date	16-May	15-May	11-May	11-May
Imazethapyr/ Imazamox, Imazamox and Metribuzin Application				
Early	2-Jun	25-May	1-Jun	31-May
Late	7-Jun	6-Jun	9-Jun	12-Jun
Sethoxydim Application (Metribuzin)				
Early	10-Jun	1-Jun	8-Jun	7-Jun
Late	12-Jun	8-Jun	15-Jun	21-Jun
Lentil Stage				
Early	3 node	2-3 node	2-3 node	3 node
Late	6-7 node	6 node	6 node	7 node
Broadleaved Weed Stage				
Early	Cotyledon- 1 leaf	Cotyledon- 1 leaf	Cotyledon- 1 leaf	Cotyledon- 2 leaf
Late	Cotyledon- 4 leaf	Cotyledon- 4 leaf	1-5 leaf	3-4 leaf
Grass Weed Stage				
Early	1-2 leaf	1-2 leaf	1-2 leaf	1-2 leaf
Late	2-5 leaf	3-5 leaf	4-6 leaf	3-5 leaf

The harvest samples were cleaned using a Carter Day Dockage Tester^{TM} and further cleaned manually when required. The samples were weighed to determine yield.

4.2.3. Statistical analysis

Lentil yield, weed biomass and weed density results were analyzed using the mixed model procedure in SAS for Windows (Version 9.1, SAS Institute Inc., Cary N.C., U.S.A.) with herbicide, application timing and the interaction between herbicide and application timing as fixed effects while site year and block were random effects. A repeated and group statement was used for site year to account for heterogeneity of variance between site years. Natural logarithmic data transformation was preformed for the grass and broadleaved weed biomass and density so that the errors were more normally distributed and more homogeneous. Least squared (LS) means were used to determine significant differences ($P<0.05$) between herbicide, application timing and the interaction between herbicide and application timing means. Single degree-of-freedom contrasts were used to explain the relationship between preplanned comparisons. Five contrasts were conducted: 1) early applied imazamox vs. early applied imazethapyr / imazamox, 2) early applied metribuzin + sethoxydim vs. late applied imazethapyr / imazamox, 3) early vs. late applied imazamox, 4) early vs. late applied imazethapyr and 5) early vs. late applied metribuzin + sethoxydim.

4.3. Results and Discussion

Climatic conditions in 2006 and 2007 varied considerably between site years and from the 30 year average (Chapter 3). The weed population and density varied throughout the site years (Table 4.2). This was likely a result of the varying climatic conditions (Table 3.2) as well as weed population differences between the sites. For example, grass weed biomass was much higher at Vanscoy than Saskatoon whereas broadleaved weed biomass was much higher at Saskatoon. Furthermore, the weed biomass was much higher in 2006 than in 2007. This was likely a result of the higher precipitation in 2006, which encouraged weed emergence and growth. However, there were no significant random effects for the weed biomass or lentil yield results (Table 4.3).

Table 4.2 Weed species population, average density and average biomass accumulation from the weedy control plot of the herbicide application studies conducted at two location in central Saskatchewan in 2006 and 2007 measured at lentil physiological maturity (BBCH =81) (Hess et al.1997).

Location	Year	Weed‡	Weed Density	Weed Biomass
			shoots m^{-2}	g m^{-2}
Saskatoon	2006	wild oat	51	304
		green foxtail	9.1	2.9
		red root pigweed	13	0.5
		wild buckwheat	1.2	3.0
		wild mustard	17	490
		Total	91	800
	2007	wild oat	110	210
		green foxtail	170	23
		red root pigweed	0.5	0.1
		wild buckwheat	4.0	2.3
		stinkweed	6.0	4.9
		wild mustard	6.5	110
		Total	300	350
Vanscoy	2006	wild oat	31	850
		green foxtail	7.0	23
		wheat	1.0	11
		red root pigweed	14	4.7
		wild buckwheat	8.0	17
		lamb's quarters	1.5	10
		Total	63	920
	2007	wild oat	88	330
		green foxtail	5.3	0.3
		Japanese brome	25	22
		wheat	0.8	2.6
		red root pigweed	1.0	0.1
		wild buckwheat	1.5	5.7
		lamb's quarters	1.5	14
		Total	120	380

‡ Weed species: wild oats (*Avena fatua* L.), green foxtail (*Setaria viridis* (L.) Beauv.), wheat (*Triticum aestivum* L.), Japanese brome (*Bromus japanicua* L.), red root pigweed (*Amaranth retroflexus* L.), wild buckwheat (*Polygonum convolvulous* L.), lamb's quarters (*Chenopodium album* L.), stinkweed (*Thalapsis arvense* L.), wild mustard (*Sinapsis arvensis* L.)

Table 4.3 Probability values from the analysis of variance of random effects for lentil yield, grass weed biomass, broadleaved weed biomass for two locations in central Saskatchewan in 2006 and 2007.

Random Effects	Broadleaved Weed Biomass§	Grass Weed Biomass§	Lentil Yield
Site Year (S)	-	0.1317	0.1416
Block (Site year)	0.2064	0.1436	0.0947
S x Application Time (T)	0.2119	0.1944	0.1843
S x Herbicide (H)	0.1655	0.1660	0.3832
S x T x H	0.1816	-	0.0851

§ Blank probability indicates the analysis of variance did not produce an estimate or probability value.

4.3.1. Broadleaved weed biomass

Broadleaved weed biomass differed significantly among the herbicide treatments (Table 4.4). Averaged over the two herbicide timings, the metribuzin + sethoxydim treatments resulted in 10 to 20 fold greater broadleaved weed biomass than imazethapyr / imazamox and imazamox (Table 4.4). Furthermore, the weed density results show that metribuzin + sethoxydim resulted in the overall highest broadleaved weed density at all site years (Tables A.1 to A.4). It was not surprising that metribuzin + sethoxydim resulted in the highest weed biomass since research indicates that metribuzin + sethoxydim provides limited control of many of the broadleaved weeds found in Saskatchewan fields (Malik and Townley-Smith, 1990). Metribuzin + sethoxydim is registered for control of broadleaved weeds such as lambs quarters, wild mustard and stinkweed but requires early application to ensure efficacy and crop safety (SMA, 2008). The weed population at all site years consisted mainly of economically important weeds in Saskatchewan including the broadleaved weeds wild buckwheat, lambs quarters and wild mustard (Table 4.2). Metribuzin + sethoxydim provided limited control of wild buckwheat and was observed to provide poor control of wild mustard when applied at the six node stage. Imazethapyr / imazamox and imazamox were more efficacious on many of the aforementioned weeds, especially wild buckwheat (SMA, 2008).

Herbicide timing did not affect broadleaved weed biomass (Table 4.4). This was unexpected based on the critical period of weed control (CPWC) for lentil (Chapter 3) and the known properties of the herbicides tested (Ball et al. 2003; Blackshaw, 1998; Shaner and

Table 4.4 Fixed effect means and analysis of variance of herbicide, herbicide application time and the interaction between herbicide and application time and the effect on lentil yield, grass weed biomass and broadleaved weed biomass. Results from four site years in central Saskatchewan are combined. Back-transformed results are presented. Letters designate significant differences between variables (*P<0.05*) within individual columns.

			Broadleaf Weed Biomass		**Grass Weed Biomass**		**Lentil Yield**	
			------ $g\ m^{-2}$ -----		**------- $g\ m^{-2}$ ------**		**------- $kg\ ha^{-1}$ ------**	
Herbicide	Imazethapyr / Imazamox		9.5	b	39	a	1200	a
	Imazamox		18	b	48	a	1100	a
	Metribuzin + Sethoxydim		190	a	8.0	b	790	b
	SE		3.8		4.3		142.0	
	p>f		*0.0001*		*0.0054*		*0.0201*	
Herbicide Application Time	2 node		38		68	a	900	
	6 node		27		8.9	b	1100	
	SE		3.6		4.2		140	
	p>f		*0.3820*		*0.0041*		*0.1256*	
Herbicide and Application Time Interaction	Imazethapyr / Imazamox	2 node	11		130	a	1040	
	Imazethapyr / Imazamox	6 node	8.0		12	b	1300	
	Imazamox	2 node	27		220	a	890	
	Imazamox	6 node	12		10	b	1200	
	Metribuzin + Sethoxydim	2 node	180		11	b	760	
	Metribuzin + Sethoxydim	6 node	200		5.9	b	810	
	SE		4.1		4.4		159.82	
	p>f		*0.3979*		*<0.0001*		*0.2503*	

Hornford, 2005; Malik and Townley-Smith, 1990; SMA, 2008). The CPWC for lentil suggests that weed control should commence at the five to six node stage and the crop must remain weed-free until the ten node stage in order to prevent yield loss. Herbicide application at the early stage should have resulted in higher weed biomass since weed growth would have likely occurred during the CPWC. None of the herbicides provided residual control of broadleaved weeds for this length of time. The late herbicide application should have prevented most weed growth throughout the CPWC. However, all herbicide treatments at their respective application timings were grouped and metribuzin + sethoxydim, imazethapyr / imazamox and imazamox were combined. Due to the variable and poor control of broadleaved weeds by metribuzin + sethoxydim the application timing results may have been affected, altering the herbicide application time effect.

The interaction between herbicide and application timing was not significant for broadleaved weed biomass (Table 4.4). However, preplanned contrasts were conducted between many of the herbicide and application combinations (Table 4.5). It was determined that metribuzin + sethoxydim applied early resulted in 22 fold greater broadleaved weed biomass than imazethapyr / imazamox applied late (Table 4.4). Surprisingly, there was no difference between the other herbicide and application timing contrasts including early applications of imazamox vs. imazethapyr / imazamox as well as early vs. late applications of imazethapyr / imazamox, imazamox and metribuzin + sethoxydim. It was expected that imazethapyr / imazamox would result in lower broadleaved weed biomass than imazamox due to its increased soil persistence, increased broadleaf activity and residual control of multiple cohorts of weeds (Ball et al. 2003; Blackshaw, 1998; Shaner and Hornford, 2005; SMA, 2008). However, these results did not occur.

4.3.2. Grass weed biomass

The interaction between herbicide and application timing was significant for grass weed biomass (Table 4.4). Early applications of imazethapyr / imazamox and imazamox resulted in grass weed biomass 11 to 38 fold greater than the other treatments (Tables 4.4 and 4.5). A

Table 4.5 Single degree comparisons of main effect relationships (Pr>*F*).

Contrast	Broadleaved Weed Biomass	Grass Weed Biomass	Lentil Yield
	g m^{-2}	g m^{-2}	kg ha^{-1}
Imazamox (early) vs. Imazethapyr / Imazamox (early)	0.122	0.305	0.327
Imazethapyr / Imazamox (late) vs. Metribuzin + sethoxydim (early)	<0.0001	0.837	0.001
Imazamox (early) vs. Imazamox (late)	0.161	<0.0001	0.031
Imazethapyr / Imazamox (early) vs. Imazethapyr / Imazamox (late)	0.547	<0.0001	0.093
Metribuzin + sethoxydim (early) vs. Metribuzin + sethoxydim (late)	0.848	0.219	0.553

proportion of the grass seedlings had not yet emerged at the early application timing and thus likely emerged during the CPWC (Tables A.5 to A.8). Late applications of imazamox and imazethapyr / imazamox resulted in levels of grass weed biomass similar to metribuzin + sethoxydim. This is interesting as sethoxydim was applied approximately one week after the late imazamox and imazethapyr / imazamox applications. Furthermore, sethoxydim is known to have higher efficacy of grass weeds than imazamox or imazethapyr / imazamox. Therefore, these results indicate the benefit of optimal herbicide timing.

4.3.3. Lentil yield

Weed control with metribuzin + sethoxydim resulted in the lowest lentil yield of the herbicide treatments regardless of timing. Averaged over herbicide application timings, metribuzin + sethoxydim resulted in the lowest lentil yield of the herbicides (Table 4.4). The timing of metribuzin + sethoxydim application did not affect lentil yield as indicated by the non-significant contrast (Table 4.5). The low yield of the metribuzin + sethoxydim treatments may be attributed to the high broadleaved weed biomass resulting from poor weed control (Table 4.4) which may have limited lentil yield potential. There was a high wild buckwheat population which metribuzin + sethoxydim did not control, especially at Vanscoy in 2006 and 2007. Wild buckwheat has vine-like branches and a climbing growth habit (Royer and Dickinson, 1999) causing harvest complications from the vines wrapping around equipment and plugging the machinery, which also compromised lentil yield. Furthermore, metribuzin + sethoxydim can be phytotoxic to lentil crops especially when applied past the four node stage (SMA, 2008). However, no crop injury was observed during this experiment.

Lentil treated with imazethapyr / imazamox or imazamox at the late application timing resulted in the highest yield. Averaged over both timings, herbicide applications of imazethapyr / imazamox and imazamox did not differ and resulted in greater lentil yield than metribuzin + sethoxydim (Table 4.4). However, the contrast indicates that late application of the imazethapyr / imazamox and imazamox herbicides resulted in the greatest lentil yield (Table 4.5). The late imazamox application resulted in approximately 310 kg ha^{-1} (25%) higher yield than the early application. Imazamox is less persistent in the soil than imazethapyr / imazamox and there was little control of late emerging weeds throughout the CPWC with the early application (Ball et al. 2003; Blackshaw, 1998; Shaner and Hornford, 2005). A similar trend (*P=0.09*) was observed with imazethapyr / imazamox application timings as the late application timing resulted in 260 kg ha^{-1} (20%) higher lentil yield than the early application. However, the yield increase resulting from late application of imazethapyr / imazamox was less than that from imazamox application timings. Imazethapyr / imazamox residues persist for a longer time in soil therefore late emerging weeds were better controlled by the early application timing (Tables A.1 to A.4). The lower lentil yields observed with early application of imazethapyr / imazamox and imazamox herbicides are probably due to the aforementioned delayed emergence in the grassy weeds.

The contrast between the early application of metribuzin + sethoxydim and the late application of imazethapyr / imazamox was significant (Table 4.5). Imazethapyr / imazamox applied at the six node stage resulted in approximately 540 kg ha^{-1} (40%) higher yield than metribuzin + sethoxydim applied at the two node stage. This difference was expected as imazethapyr / imazamox is known to provide better weed control (Malik and Townley-Smith, 1990; SMA, 2008).

Weed control is known to be one of the most important limitations in conventional lentil production (McDonald et al. 2007) due to the poor competitive ability of lentil and lack of efficacious herbicides for adequate control of both grass and broadleaved weeds (Friesen and Wall, 1986; Wall and McMullan, 1994). The results from this experiment further prove the need for adequate weed control in lentil production. Metribuzin is the only option for POST broadleaved weed control in conventional lentil (SMA, 2008) but was clearly shown to provide inadequate control of broadleaved weeds regardless of application timing and resulted in poor lentil yield. Therefore, for conventional lentil production all efforts should be made with integrated weed management systems to control weeds prior to seeding and emergence of lentil. These results show that timely application of imazethapyr / imazamox or imazamox on IMI-tolerant lentil can result in improved control of broadleaved weeds and subsequently higher lentil yield.

4.4. Conclusion

The objective of this study was to validate the CPWC concept by testing application timings of herbicides differing in efficacy and residual control. The results indicated that the type of herbicide and application timing had a significant effect on lentil yield, grass weed biomass and broadleaved weed biomass. Application of imazethapyr / imazamox and imazamox at the approximate onset of the CPWC (five to six node stage) resulted in the greatest yield and lowest weed biomass. Therefore, the hypothesis was generally correct. However, it was not expected that imazamox would result in similar yield to imazethapyr / imazamox because of the prediction for reduced residual weed control. However, this research did not show residual weed control differences between imazethapyr / imazamox and imazamox. Herbicide application before the CPWC resulted in lower yield and higher weed biomass than application at the beginning of the CPWC. Therefore, imazethapyr / imazamox or imazamox should be applied at the five to six node stage of lentil to attain the weed-free period required for the CPWC.

5.0 General Discussion

5.1. Optimizing Weed Control in Lentil

The overall objective of this research was to determine the optimal weed control timing and method to maximize lentil yield. There were two main objectives for the research. The first was to determine the critical period of weed control (CPWC) in lentil. The second objective was to determine the best herbicide usage to attain satisfactory weed control throughout the CPWC.

The CPWC for lentil grown in western Canada was determined to be from the five node stage up to the 10 node stage. These results lead to the acceptance of the primary hypothesis that lentil would require an extended CPWC with a delayed beginning and extending late into the reproductive period. Weed growth throughout this period resulted in significant yield loss whereas weed growth outside of this period did not.

Weed biomass accumulation and prevention were inversely related to the lentil yield results. Significant weed biomass accumulation began at the five node stage of lentil. The weed-free period required to prevent significant weed biomass accumulation was up to the 10 node stage of lentil which was also observed to correspond with canopy closure. The beginning of the CPWC is a function of weed growth and competition whereas the end is a function of the crop's competitive ability (Knezevic et al. 2002). Therefore, an alternative way to describe the CPWC in lentil is from the onset of significant weed biomass accumulation until canopy closure. Weed competition was essentially the only factor that affected the onset of the CPWC; the crop had little influence. Therefore, in situations where there is insignificant or no weed growth there may be no CPWC (Martin et al. 2001). Conversely, in situations where the weeds emerge before the crop or there is heavy weed competition, the onset of the CPWC may began early. The end of the CPWC however, is affected by the crop. The end of the CPWC is determined by the level of competitiveness of the crop with the weeds. Since lentil is a poorly competitive crop (Blackshaw et al. 2002) it required an extended weed-free period.

Research was also conducted to investigate the optimal herbicide to use in relation to the CPWC (Chapter 4). Imazethapyr / imazamox and imazamox applied at the six node stage of lentil (late) resulted in the overall highest yield. Imazethapyr / imazamox and imazamox resulted in the best broadleaved weed control and provided grass weed control comparable to metribuzin

+ sethoxydim when applied late. Most interestingly however, imazethapyr / imazamox applied late resulted in lower broadleaved weed biomass and higher yield than metribuzin + sethoxydim. These herbicides represent the weed control systems used in IMI-tolerant and conventional lentil, respectively. The grass weed biomass was comparable, however to imazethapyr / imazamox and imazamox. It can be concluded that the IMI-tolerant lentil herbicide system can result in much higher yield when weed control timing and method is optimal.

The hypothesis for the herbicide application and timing experiment was largely true. It was hypothesized that delayed imazethapyr / imazamox application timing would result in the lowest weed biomass and highest lentil yield due to its increased soil activity. However, both imazethapyr / imazamox and imazamox achieved these results. This was surprising as imazamox does not provide as much residual soil activity as imazethapyr / imazamox (Blackshaw, 1998; Ball et al. 2003; Shaner and Hornford, 2005) and it was thought that weeds would emerge throughout the CPWC. However, the weed density results were largely inconclusive and did not provide an indication of the residual control provided by either herbicide. Both herbicides provided excellent control of broadleaved and grass weeds when applied at the six node stage and resulted in increased yield. Therefore, based on the CPWC and the herbicide application results, the application of imazethapyr / imazamox or imazamox at the onset of weed biomass accumulation is recommended to ensure a weed-free period throughout the CPWC to maximize lentil yield. However, if weeds do emerge throughout this period a second application of imazamox, imazethapyr / imazamox or a graminicide may be warranted based on the CPWC.

The results from this research provide further evidence that weed control is beneficial to improving lentil yield. Understanding the effect of weed competition on crop yield is useful for implementing management decisions. These results also show the benefit of herbicide tolerant lentil versus conventional lentil as better broadleaf weed control can be achieved with IMI herbicides, which also provide improved crop safety and a wider window for application timing.

The CPWC in lentil has been studied in other regions of the world. Mohamed et al. (1997) and Singh et al. (1996) studied this concept in Sudan and Jordan, respectively. However, as mentioned in Chapter 3, the results of these studies cannot be applied to western Canada since they were conducted in winter growing seasons with different weed control practices and different weed spectrums. They do however, indicate the importance of POST early season weed removal as was realized with this research.

The beginning of the CPWC is similar amongst many crops. The onset of the CPWC for soybeans (Knezevic et al. 2003), corn (Hall et al. 1992; Halford et al. 2001; Williams, 2006), canola (Martin et al. 2001), chickpea (Mohammadi et al. 2005) and field pea (Harker et al. 2001) occurred during the first two to four weeks after sowing (Mohamed et al. 1997). The CPWC for lentil was also determined to commence within this time frame (data not shown) (Chapter 3). This is interesting as these crops are physiologically different with different competitive abilities. This indicates that the significance of the duration of weed interference and that the beginning of the CPWC may not be a function of the crop's competitive ability but instead is a function of the onset of early weed growth. Across all studies weeds were causing crop yield loss within approximately the same time frame.

While the CPWC is a useful tool for weed management decisions, it is a theoretical concept with limitations. Knezevic et al. (2002) and Rajcan and Swanton (2001) describe many of the limitations, including both crop and weed characteristics. Weed characteristics including morphology, physiology and development, as well as density and relative time of emergence can affect the CPWC and therefore can result in temporal- and spatial- specific results. For example, I was fortunate to have conducted this research in 2006 and 2007 in that precipitation and temperatures were sufficient to promote early season weed growth in both years. If the research had been conducted in 2008 or 2009 the results would likely have been drastically different. Both 2008 and 2009 were characterized by low precipitation and cold temperatures that did not encourage weed growth. In fact, in these years a large proportion of seedlings emerged late in the growing season causing producers major weed control problems. Therefore, the research was conducted in an ideal environment to understand lentil-weed competition and essentially represent a worst case scenario where potential weed competition was maximized. The CPWC determined in this study can be considered a conservative estimate and therefore the CPWC from the five to ten node stage (significant weed biomass accumulation to lentil canopy closure) encompasses all environments. The environment can have an effect on the crop-weed interaction and its influence on competition. In conditions that promote weed emergence, such as were observed during the present study, the CPWC is long however, under drought conditions and/or cool temperatures weed emergence would be retarded and the CPWC could be shortened or might not exist. For example, Marten et al. (2001) found that in some situations the CPWC for canola could not be determined because of negligible weed emergence and the lack of yield response to weed interference.

IMI-tolerant lentil is a valuable tool for lentil producers because of the increased efficacy and improved crop safety afforded by the IMI herbicides. However, the utility of IMI herbicides is compromised by the rapid increase in ALS inhibitor (group two) herbicide resistance of economically important weed species (Beckie et al. 2008). ALS inhibitors are one of the highest risk herbicide groups for the selection of herbicide resistance and over 90 resistant weed species have been reported globally (Heap, 2010). Over the past 20 years ALS inhibitor resistant kochia (*Kochia scoparia* L.), wild mustard, stinkweed, shepherd’s purse, cleavers (*Galium aparine* L.), and wild oat, amongst others, have been identified in western Canada (Beckie et al. 2008). This drastic increase in resistant populations has the potential to limit the use of group two herbicides including IMI’s. This is of utmost concern as IMI herbicides are essentially the only option for effective weed control in tolerant lentil and field pea, important pulse crops in western Canada. In fact, lentil and field pea producers have resorted to metribuzin application to control ALS resistant wild mustard and stinkweed and are therefore making at least two herbicide applications to control all weeds. ALS inhibitor herbicides need to be properly managed and should be preserved for pulse crops. Herbicides are a non-renewable resource (Beckie, 2006) and the loss of IMI herbicides due to resistance would be detrimental to pulse crop production.

5.2. Future Research

This research was the first study to determine the CPWC for lentil in western Canada. However, more research is needed to completely understand all aspects of lentil-weed competition and the CPWC. For example, quantifying the effect of the relative time of crop and weed emergence would be beneficial. The relative time of weed and crop emergence is known to play a large role in competition relationships (Swanton et al. 1999). The effect of weed emergence prior to crop emergence and vice versa could affect producer’s overall weed management programs and determine the need for a pre-seeding / pre-emergent herbicide application. Another area of research where more insight is required is the effect of weed species and density on lentil yield. The weed density was highly variable within and between the studies and direct inferences regarding density could not be made. A study identifying the effect of a quantified weed density, such as McDonald et al. (2007) conducted with lentil as the crop and canola as the weed, would help to understand the requirement and type of weed control. Furthermore, in this proposed study it would be interesting to identify a competition threshold with weeds common in lentil production to provide further information on crop-weed relationships. Adjusting the crop density for further CPWC studies would provide a better understanding of the effect weeds have on the start and end of the CPWC. Previous research has indicated that increased crop densities are more competitive with weeds (Boerboom and Young, 1995; Baird et al. 2009) and thus weed control can be delayed or eliminated.

It would also be interesting to conduct a similar experiment not using crop stage as the main identifier for weed control timing, but using weed stage as the guide. In this study, the CPWC of lentil was defined as the beginning of significant weed biomass accumulation to the timing of canopy closure (ie. the 10 node stage).This has much more biological meaning in terms of defining the beginning of the CPWC since it is largely influenced by weed competition not by crop characteristics. Furthermore, defining the CPWC in this way could be used in different environments and under different management practices. However, crop safety would be of concern as many of the herbicides are only registered for the early stages of crop development. Similarly, weeds generally must be small for adequate control.

The effect of herbicide and application time on weed density and biomass should also be further investigated. The effect of imazethapyr / imazamox, imazamox and metribuzin + sethoxydim on weed density over time was discussed in Chapter 4 with the intention of determining the length of residual control. However, these results were largely inconclusive. Therefore, more research should be conducted in a more controlled environment to fully realize the residual control of imazethapyr / imazamox, imazamox and metribuzin + sethoxydim and make more conclusive recommendations for the CPWC. However, the weed biomass and lentil yield results were generally as expected. These results show the benefit of IMI-tolerant lentil to be improved weed control and a longer application period which can be achieved with the application of imazethapyr / imazamox or imazamox, thus allowing for weed control throughout the CPWC.

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7.0 APPENDIX

7.1. Appendix A: Grass and broadleaved weed density measurements

Table A.1 Broadleaved weed density (broadleaved weeds m^{-2}) response to herbicide, herbicide application timing and their interaction at Saskatoon, 2006 measured on June 2, June 16, June 26 as well as at crop physiological maturity (PM). Significant differences are designated with different letters (*P<0.05*).

			2-Jun	16-Jun	26-Jun		PM*	
Herbicide (H)	Imazethapyr / imazamox		1.3	0.6	0.4	c	0.9	b
	Imazamox		1.9	1.2	0.8	b	1.8	a
	Metribuzin + sethoxydim		1.7	1.0	1.5	a	2.3	a
		SE	0.4	0.5	0.5		0.4	
		P>F	*0.3329*	*0.113*	*0.0004*		*0.0073*	
Herbicide Timing (T)	2 node		1.8	0.8	0.9		1.8	
	6 node		1.4	1.0	0.6		1.4	
		SE	0.4	0.4	0.4		0.4	
		P>F	*0.2791*	*0.2795*	*0.1337*		*0.2703*	
H x T Interaction	Imazethapyr / imazamox	2 node	1.3	0.4	2.3		1.2	
	Imazethapyr / imazamox	6 node	1.3	0.9	1.0		0.7	
	Imazamox	2 node	1.8	0.9	0.4		1.8	
	Imazamox	6 node	2.0	1.5	0.4		1.7	
	Metribuzin + sethoxydim	2 node	2.4	1.2	0.9		2.5	
	Metribuzin + sethoxydim	6 node	1.2	0.9	0.7		2.2	
		SE	0.5	0.5	0.5		0.5	
		P>F	*0.2609*	*0.2652*	*0.3764*		*0.5725*	

*weeds were counted at physiological maturity at the same time weed biomass was measured

Table A.2 Broadleaved weed density (broadleaved weeds m^{-2}) response to herbicide, herbicide application timing and their interaction at Vanscoy, 2006 measured on May 31, June 6, June 29 as well as at crop PM. Significant differences are designated with different letters (*P<0.05*).

			31-May		6-Jun	29-Jun	PM*	
Herbicide (H)	Imazethapyr / imazamox		0.8		0.9	1.4	2.1	b
	Imazamox		1.0		1.3	1.5	3.5	ab
	Metribuzin + sethoxydim		0.8		1.5	0.9	4.3	a
		SE	0.5		0.4	0.4	0.4	
		P>F	*0.7152*		*0.1134*	*0.0843*	*0.0276*	
Herbicide Timing (T)	2 node		0.9		0.8	1.2	2.9	
	6 node		0.8		1.7	1.2	3.4	
		SE	0.4		0.4	0.4	0.4	
		P>F	*0.9426*		*0.0019*	*0.9686*	*0.4792*	
H x T Interaction	Imazethapyr / imazamox	2 node	1.1	a	0.5	1.4	1.7	
	Imazethapyr / imazamox	6 node	0.5	b	1.5	1.3	2.6	
	Imazamox	2 node	1.1	a	0.9	1.3	3.5	
	Imazamox	6 node	0.9	a	1.7	1.7	3.4	
	Metribuzin + sethoxydim	2 node	0.5	b	1.1	1.0	4.1	
	Metribuzin + sethoxydim	6 node	1.3	a	2.1	0.8	4.0	
		SE	0.5		0.5	0.5	0.5	
		P>F	*0.0453*		*0.6806*	*0.6881*	*0.6501*	

*weeds were counted at physiological maturity at the same time weed biomass was measured

Table A.3 Broadleaved weed density (broadleaved weeds m^{-2}) response to herbicide, herbicide application timing and their interaction at Saskatoon, 2007 measured on June 1, June 8, June 21, June 28, July 4, July 13, July 25 as well as at crop PM. Significant differences are designated with different letters (P<0.05).

			1-Jun	8-Jun	21-Jun	28-Jun	4-Jul	13-Jul	25-Jul	PM*
Herbicide (H)	Imazethapyr / imazamox		4.0	3.3	2.1	0.8	1.1	0.9	0.5	1.6
	Imazamox		3.2	2.9	2.8	1.2	0.8	1.1	0.4	1.8
	Metribuzin + sethoxydim		3.8	3.4	6.6	1.0	0.9	1.0	0.5	2.3
		SE	0.4	0.5	0.6	0.6	0.6	0.6	0.5	0.5
		P>F	*0.5605*	*0.9371*	*0.0031*	*0.3459*	*0.6009*	*0.8569*	*0.5453*	*0.4738*
Herbicide Timing (T)	2 node		3.5	1.5 b	3.9	1.0	0.9	0.9	0.4	1.8
	6 node		3.9	6.8 a	2.9	1.0	1.0	1.2	0.5	1.9
		SE	0.4	0.5	0.6	0.6	0.6	0.6	0.4	0.5
		P>F	*0.531*	*0.0004*	*0.211*	*0.8752*	*0.6856*	*0.4572*	*0.4679*	*0.8034*
H x T Interaction	Imazethapyr / imazamox	2 node	3.4	1.6	2.6	0.9	0.9	0.8	0.5	1.6
	Imazethapyr / imazamox	6 node	4.8	7.1	1.6	0.7	1.5	1.0	0.4	1.5
	Imazamox	2 node	4.1	1.7	4.3	1.2	0.9	1.7	0.4	2.2
	Imazamox	6 node	2.5	5.2	1.8	1.2	0.8	0.8	0.4	1.5
	Metribuzin + sethoxydim	2 node	3.0	1.3	5.5	0.9	1.0	0.5	0.4	1.7
	Metribuzin + sethoxydim	6 node	4.8	8.5	8.0	1.0	0.9	2.1	0.7	3.1
		SE	0.5	0.6	0.7	0.6	0.7	0.7	0.5	0.5
		P>F	*0.074*	*0.7032*	*0.1336*	*0.8489*	*0.472*	*0.093*	*0.411*	*0.2988*

*weeds were counted at physiological maturity at the same time weed biomass was measured

Table A.4 Broadleaved weed density (broadleaved weeds m^{-2}) response to herbicide, herbicide application timing and their interaction at Vanscoy, 2007 measured on June 1, June 10, June 22, July 2, July 12, July 19 as well as at crop PM. Significant differences are designated with different letters (*P<0.05*).

			1-Jun	10-Jun	22-Jun	2-Jul		12-Jul	19-Jul		PM*	
Herbicide (H)	Imazethapyr / imazamox		2.8	7.9	1.2	4.9		1.0	1.0		2.5	b
	Imazamox		3.0	8.2	1.5	2.7		1.3	1.7		4.5	ab
	Metribuzin + sethoxydim		3.1	9.2	1.6	3.9		2.0	2.1		5.4	a
		SE	0.5	0.4	0.6	0.5		0.5	0.5		0.6	
		P>F	*0.9569*	*0.834*	*0.915*	*0.4021*		*0.3543*	*0.1228*		*0.04*	
Herbicide Timing (T)	2 node		2.9	6.9		2.2	b	1.0	1.1	b	4.4	
	6 node		3.0	10.3		6.4	a	1.9	2.1	a	3.5	
		SE	0.4	0.4		0.5		0.5	0.5		0.5	
		P>F	*0.8254*	*0.0658*		*0.0055*		*0.1139*	*0.0493*		*0.3341*	
H x T Interaction	Imazethapyr / imazamox	2 node	2.5	6.9		1.2		1.1	1.0		3.2	
	Imazethapyr / imazamox	6 node	3.2	9.2		6.4		1.0	1.0		1.9	
	Imazamox	2 node	2.4	6.8		3.2		0.7	1.3		4.4	
	Imazamox	6 node	3.7	9.9		4.7		2.2	2.2		4.5	
	Metribuzin + sethoxydim	2 node	3.9	6.9		2.7		1.3	1.1		6.0	
	Metribuzin + sethoxydim	6 node	2.4	12.2		8.9		3.0	4.0		4.8	
		SE	0.5	0.5		0.6		0.6	0.5		0.6	
		P>F	*0.3906*	*0.8591*		*0.3032*		*0.3961*	*0.2395*		*0.6809*	

*weeds were counted at physiological maturity at the same time weed biomass was measured

Table A.5 Grass weed density (grass weeds m^{-2}) response to herbicide, herbicide application timing and their interaction at Saskatoon, 2006 measured on June 2, June 16, June 26 as well as at crop PM. Significant differences are designated with different letters (*P<0.05*).

			2-Jun	16-Jun		26-Jun		PM*	
Herbicide (H)	Imazethapyr / imazamox		2.3	3.5	ab	1.6	a	2.2	a
	Imazamox		2.3	3.1	b	1.8	a	2.2	a
	Metribuzin + sethoxydim		2.3	4.9	ab	0.7	b	0.5	b
		SE	0.2	0.4		0.5		0.5	
		P>F	*0.893*	*0.0593*		*0.0115*		*0.0001*	
Herbicide Timing (T)	2 node		2.3	3.9		1.8	a	1.8	a
	6 node		2.3	3.6		0.9	b	1.0	b
		SE	0.1	0.4		0.4		0.4	
		P>F	*0.8356*	*0.6075*		*0.0155*		*0.0292*	
H x T Interaction	Imazethapyr / imazamox	2 node	2.2	3.6		3.0		3.4	
	Imazethapyr / imazamox	6 node	2.4	3.4		0.8		1.4	
	Imazamox	2 node	2.2	3.0		3.2		3.6	
	Imazamox	6 node	2.5	3.3		1.1		1.4	
	Metribuzin + sethoxydim	2 node	2.6	5.6		0.6		0.5	
	Metribuzin + sethoxydim	6 node	2.0	4.2		0.7		0.5	
		SE	0.2	0.4		0.5		0.5	
		P>F	*0.0928*	*0.5547*		*0.0620*		*0.1990*	

*weeds were counted at physiological maturity at the same time weed biomass was measured

Table A.6 Grass weed density (grass weeds m^{-2}) response to herbicide, herbicide application timing and their interaction at Vanscoy, 2006 measured on May 31, June 6, June 29 as well as at crop PM. Significant differences are designated with different letters (*P<0.05*).

			31-May	6-Jun		29-Jun		PM*	
Herbicide (H)	Imazethapyr / imazamox		1.9	1.4		0.5		0.7	b
	Imazamox		1.5	1.3		0.7		1.4	a
	Metribuzin + sethoxydim		1.9	1.6		0.5		0.7	b
		SE	0.2	0.4		0.4		0.5	
		P>F	*0.4912*	*0.6809*		*0.4191*		*0.0568*	
Herbicide Timing (	2 node		1.8	0.7	b	0.7	a	1.4	a
	6 node		1.8	2.9	a	0.4	b	0.6	b
		SE	0.2	0.4		0.4		0.5	
		P>F	*0.8387*	*<0.0002*		*0.0074*		*0.0022*	
H x T Interaction	Imazethapyr / imazamox	2 node	2.2	0.5	c	0.8		0.9	
	Imazethapyr / imazamox	6 node	1.7	3.9	a	0.4		0.6	
	Imazamox	2 node	1.4	0.9	c	1.0		2.5	
	Imazamox	6 node	1.7	2.0	b	0.5		0.8	
	Metribuzin + sethoxydim	2 node	1.7	0.8	c	0.5		1.3	
	Metribuzin + sethoxydim	6 node	2.0	3.2	ab	0.4		0.4	
		SE	0.3	0.5		0.5		0.5	
		P>F	*0.3592*	*0.04*		*0.3621*		*0.3514*	

*weeds were counted at physiological maturity at the same time weed biomass was measured

Table A.7 Grass weed density (grass weeds m^{-2}) response to herbicide, herbicide application timing and their interaction at Saskatoon, 2007 measured on June 1, June 8, June 21, June 28, July 4, July 13, July 25 as well as at crop PM. Significant differences are designated with different letters (*P<0.05*).

			1-Jun		8-Jun		21-Jun	28-Jun	4-Jul	13-Jul	25-Jul	PM*
Herbicide (H)	Imazethapyr / imazamox		3.5		1.7	b	0.4	0.4	0.4	0.4	0.4	0.9
	Imazamox		3.6		1.4	b	0.4	0.5	0.4	0.4	0.4	0.4
	Metribuzin + sethoxydim		5.1		4.8	a	0.4	0.4	0.4	0.4	0.4	0.4
		SE	0.4		0.4		0.4	0.4	0.4	0.4	0.4	0.5
		P>F	*0.1626*		*0.0002*		*0.3911*	*0.2156*	*0.5486*	*n/a*	*0.6147*	*0.0666*
Herbicide Timing (T)	2 node		3.4	a	1.0	b	0.4	0.4	0.4	0.4	0.4	0.6
	6 node		4.8	b	4.7	a	0.4	0.4	0.4	0.4	0.4	0.5
		SE	0.4		0.4		0.4	0.4	0.4	0.4	0.4	0.5
		P>F	*0.0583*		*<0.0001*		*0.3332*	*0.5745*	*0.1347*	*n/a*	*0.1744*	*0.4156*
H x T Interaction	Imazethapyr / imazamox	2 node	2.6		0.6	b	0.4	0.4	0.4	0.4	0.4	1.1
	Imazethapyr / imazamox	6 node	4.9		4.9	a	0.4	0.4	0.5	0.5	0.4	0.7
	Imazamox	2 node	3.2		0.4	b	0.4	0.6	0.4	0.4	0.4	0.5
	Imazamox	6 node	4.1		4.3	a	0.4	0.4	0.5	0.5	0.4	0.4
	Metribuzin + sethoxydim	2 node	4.8		4.4	a	0.4	0.4	0.4	0.4	0.4	0.4
	Metribuzin + sethoxydim	6 node	5.4		5.2	a	0.4	0.4	0.4	0.4	0.4	0.4
		SE	0.5		0.5		0.4	0.4	0.4	0.4	0.4	0.5
		P>F	*0.4383*		*0.0008*		*0.3911*	*0.7253*	*0.5486*	*n/a*	*0.6147*	*0.8144*

*weeds were counted at physiological maturity at the same time weed biomass was measured

Table A.8 Grass weed density (grass weeds m^{-2}) response to herbicide, herbicide application timing and their interaction at Vanscoy, 2007 measured on June 1, June 10, June 22, July 2, July 12, July 19 as well as at crop PM. Significant differences are designated with different letters ($P<0.05$).

		1-Jun	10-Jun	22-Jun	2-Jul	12-Jul	19-Jul	PM*
Imazethapyr / imazamox		10.7	13.5 b	0.8	0.8	1.3	0.8	5.8 a
Imazamox		13.4	14.0 b	0.8	1.0	1.0	0.8	5.1 a
Metribuzin + sethoxydim		14.3	21.2 a	0.4	0.6	1.0	0.5	0.5 b
	SE	0.4	0.4	0.5	0.5	0.5	0.5	0.5
	P>F	*0.0977*	*0.005*	*0.2776*	*0.3186*	*0.684*	*0.3055*	*<0.0001*
2 node		13.6	15.4		1.2 a	1.0	0.7	5.1 a
6 node		11.8	16.4		0.5 b	1.1	0.7	1.2 b
	SE	0.4	0.4		0.4	0.5	0.4	0.4
	P>F	*0.15*	*0.564*		*0.001*	*0.797*	*0.9722*	*<0.0001*
Imazethapyr / imazamox	2 node	11.9	12.2		1.3	1.4	0.9	14.2 a
Imazethapyr / imazamox	6 node	9.6	14.9		0.4	1.2	0.7	2.3 b
Imazamox	2 node	12.9	13.4		1.3	0.8	0.6	15.1 a
Imazamox	6 node	13.9	14.7		0.7	1.2	1.0	1.7 b
Metribuzin + sethoxydim	2 node	16.6	22.3		1.1	1.0	0.6	0.6 c
Metribuzin + sethoxydim	6 node	12.3	20.1		0.4	1.0	0.4	0.4 c
	SE	0.4	0.4		0.5	0.5	0.5	0.5
	P>F	*0.3323*	*0.5037*		*0.5944*	*0.7755*	*0.2929*	*0.0197*

*weeds were counted at physiological maturity at the same time weed biomass was measured.