The Evaluation of New Harvest Aid Herbicides for Dry Bean (*Phaseolus vulgaris* L.) Production in Manitoba.

BY

KRISTINE APRIL WADDELL

A Thesis Submitted to the Faculty of Graduate Studies of

The University of Manitoba

In Partial Fulfillment of the Requirements For the Degree of

MASTER OF SCIENCE

Department of Plant Science

University of Manitoba

Winnipeg, Manitoba

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THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

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ABSTRACT

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Edible dry beans are an important pulse crop to Canadian producers. Seed maturity at the time of harvest is critical in dry bean production. Spatial variation and an indeterminate growth habit often result in uneven maturation within and among plants in a field. To alleviate uneven maturation, a broad spectrum herbicide can be used to desiccate the bean plants and provide late season weed control. Application timing of harvest aids is critical as it may affect final yield or result in unacceptable herbicide residues in the seed. Glyphosate is the most commonly used harvest aid and provides uniform dry down of the beans, excellent weed control and also controls regrowth of the bean plant. When glyphosate is applied prior to physiological maturity of the bean plant there is a potential for unacceptable levels of glyphosate residue to accumulate in the seed. Glyphosate residue in the seed can be problematic if residue levels above internationally accepted maximum residue limits are detected. The objectives of this research were to evaluate new and existing harvest aid herbicide options for Canadian dry bean growers that will provide fast, uniform dry down of bean plants, effectively control weeds present at the time of application and ensure chemical residues in seed are consistently below maximum residue limits. Field experiments were conducted at Carman, Manitoba to determine the effect of tank-mixing different contact herbicides with glyphosate and time of application of harvest aid herbicides on residue accumulation in dry bean seed and the effect of tank-mixing a contact herbicide with glyphosate on weed control. Applications of harvest aids containing mixtures of glyphosate and carfentrazone-ethyl, diquat, flumioxazin, glufosinate or saflufenacil did not adversely affect yield. Carfentrazone-ethyl in mixture with glyphosate was the least effective harvest aid herbicide and did not fully desiccate plant parts or reduce glyphosate residues in the seed to less than 2 ppm. Saflufenacil, diquat, flumioxazin, and glufosinate in mixture with glyphosate effectively desiccated all plant parts and reduced glyphosate residue accumulation in the seed compared to carfentrazone-ethyl in mixture with glyphosate or glyphosate alone. Saflufenacil in mixture with glyphosate provided the most consistent efficacy on three weed species. Time of application of harvest aid herbicides influenced residue accumulation and yield; however, all harvest aids applied at or after 75% pod colour change (PCC) had no negative effect on yield and significantly reduced the risk of residue accumulation.

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GLOSSARY OF TERMS

AMPA……………………...Aminomethylphosphonic acid

AUDPC……………………Area under the desiccation progress curve

MC…………………………Moisture content

PCC………………………...Pod colour change

PPM………………………...Parts per million

1.0 INTRODUCTION

Edible dry beans are an important pulse crop to Canadian producers. Canada is the fifth largest exporter of dry beans with 90% of dry beans produced being exported (Goodwin, 2003). This Canadian production accounts for approximately 10% of the world's dry bean exports and is valued at $200 million annually (Food and Agriculture Organization 2013).

Seed maturity at the time of harvest is crucial in dry bean production. Spatial variation and an indeterminate growth habit often result in uneven maturation within and among plants in a field. To alleviate uneven maturation, growers generally use a broad spectrum herbicide to assist harvest by desiccating the bean plants and providing late season weed control (Anonymous 2006). Herbicides currently registered and used by producers for dry bean pre-harvest application are glyphosate, carfentrazone-ethyl, glufosinate ammonium, saflufenacil and diquat (Anonymous 2013). Application timing of a harvest aid herbicide is critical as it may affect yield or result in unacceptable levels of herbicide residues in the seed (Cessna et al. 2000; Cessna et al. 2002).

Glyphosate is the most commonly used harvest aid herbicide by producers in dry bean production in Canada. Glyphosate adequately provides producers uniform dry down of the crop, excellent late season weed control and effectively controls crop regrowth following harvest (Atkinson and Grossbard 1985; Baylis 2000; Franz et al. 1997;

Hartzler et al. 2006; Sharma 1986). When applied at the appropriate bean growth stage (80% pod colour change [PCC], 30% seed moisture) (Wilson and Smith 2002), glyphosate translocates throughout the plant, causing plant mortality through the disruption of the enolpyruvyl-shikimate phosphate (EPSP) synthase enzyme (Baylis 2000; Franz et al. 1997; Hartzler et al. 2006; Sharma 1986). With the chemical translocation throughout the plant, enzyme production crucial for growth and development is disrupted causing plant mortality (Franz et al. 1997). When applied too early during seed filling and maturation, glyphosate still translocates throughout the plant and causes mortality; however, increased levels of glyphosate residue can accumulate in the harvested bean seed. Glyphosate residue in the seed can be problematic if residue levels are detected above internationally accepted maximum residue limits of 2 parts per million (ppm) (Food and Health Organization 2010; Foreign Agricultural Service 2012) since Japanese and European export markets will not accept harvested products that contain these unacceptable residues. In 2008, a shipment of Canadian dry beans (variety Otebo) was rejected by Japan due to the detection of glyphosate residues above the maximum accepted level (Sprague 2009). This incident has the potential to severely impact the export of Canadian produced dry beans to Japan in the future.

New restrictions on glyphosate use have now been imposed as a result of this incident and because of these; producers are left with limited harvest aid herbicide options. Other registered harvest aids are contact herbicides such as diquat, glufosinate, carfentrazone-ethyl and flumioxazin. These harvest aid herbicides often provide inadequate control of difficult to manage annual, winter-annual and perennial weeds at harvest time. These herbicides are also considerably more expensive than glyphosate (Anonymous 2013). New harvest aid options are required for producers as alternatives to glyphosate. There are new chemicals currently available in the market that have the potential to act as desirable harvest aid herbicides but these are not registered for pre-harvest application. Products such as saflufenacil require evaluation to determine if they are capable of providing fast, uniform dry down of bean plants, effectively controlling weeds present at harvest while eliminating chemical residues from the seed as per international maximum residue level standards.

2.0 LITERATURE REVIEW

2.1 Common Dry Bean

2.1.1 History

The common bean (*Phaseolus vulgaris* L.) is part of the *Leguminosae* family, and is known most commonly in North America as dry bean or field bean (Graham and Ranalli 1997; Laing et al. 1985). The term dry bean refers to different market classes of bean including pinto, white pea (navy), cranberry, black, red kidney, great northern, dutch brown, pink and small red (Hardman et al. 1990; Anonymous 2002). Market classes are separated by seed size and colour. In North America, the pinto bean market class accounts for 40% of annual bean production and is the most commonly grown market class of dry bean (Anonymous 2000b; Hardman et al. 1990).

The dry bean is considered to be among one of the first crops domesticated by indigenous people of Central and South America over 7,000 years ago (Gepts 1998; Hardman et al. 1990; Kaplan 1965; Myers 2002). Dry beans are produced on every continent except Antarctica, with the majority of the crop produced in the Americas, eastern Asia, east Africa and west and southeast Europe (Fageria and Santos 2008; Food and Health Organization 2010; Graham and Ranalli 1997).

2.1.2 Plant Morphology

Dry beans are commonly classified by plant morphology type. Bush type plants have a determinate growth habit and are well suited for narrow row (solid seeded) bean production whereas vine type plants have an indeterminate growth habit and are better suited to row crop production (Fageria and Santos 2008; Graham and Ranalli 1997; Laing et al. 1985). Beans with a determinate growth habit cease vegetative growth once the reproductive stage of their life cycle has begun (ie. flowering). An indeterminate growth habit means that bean plants will continue to flower and set seed for as long as the conditions are favorable for reproduction (Anonymous 2006; Fageria and Santos 2008; Graham and Ranalli 1997; Laing et al. 1985). Growth habits in dry beans are diverse and have been subdivided into four categories including: TYPE I - determinate upright bush, TYPE II - indeterminate, upright short vine, narrow plant profile, TYPE III - indeterminate, prostrate vine, TYPE IV - indeterminate with strong climbing tendencies (Graham and Ranalli 1997; Schoonhoven and Voysest 1991).

Dry beans exhibit epigeal germination. Epigeal germination causes the cotyledons to be pulled out of the ground due to elongation of the hypocotyl (Dale 1964; Fageria and Santos 2008; Gates 1951; Graham and Ranalli 1997; Kaplan 1981; Miller et al. 2002). The cotyledons function as leaves until the true leaves emerge. The first true leaves are single leaves (unifoliate) and all succeeding leaves are arranged in a cluster of three leaflets referred to astrifoliate leaves (Adams 1967; Anonymous 2006; Dale 1964).

Dry beans are a warm season crop and require 90 to 120 days to reach maturity (Fageria and Santos 2008; Hardman et al. 1990; Miller et al. 2002). Frost is always a concern in dry bean production because of the sensitivity of the emerging seedlings to cold temperatures. Beans are also sensitive to frost in the fall but can escape damage from the cold temperatures if the plants are sufficiently mature. The length of the frost free period is a major limitation to dry bean production in western Canada (Anonymous 2006; Hardman et al. 1990; Miller et al. 2002). Ideal seeding conditions are when soil temperatures are above 10°C at planting depth and the risk of a killing frost has passed (Hardman et al. 1990; Miller et al. 2002;).

Dry beans can be successfully cultivated in many soil types but perform best in medium textured soils that offer good water movement, water holding capacity and drainage (Anonymous 2006; Miller et al. 2002). Planting on heavy clay soils should be avoided due to poor drainage, waterlogging, and prolonged cool soil temperatures (Anonymous 2000b; Hardman et al. 1990; Myers 2002; Park 1985).

Dry beans are sensitive to poor soil conditions. Soils suffering from compaction and poor drainage tend to be oxygen deficient which can inhibit germination and growth (Brereton et al. 1986; Hardman et al. 1990; Park 1985). Also, soils that are saline or have a pH of 7.5 or higher can be harmful to bean plants and should be avoided (Delgado et al. 1993). Beans respond favorably to good moisture during the growing season, however, do not tolerate flooding and any prolonged exposure to these conditions has the potential to severely stunt plant growth or cause plant death (Anonymous 2000b; Anonymous 2006; Miller et al. 2002).

2.1.3 Global Dry Bean Production

The dry bean is considered to be one of the most important pulse crops in the world. In 2011, the global production of dry beans was 23,250,253 metric tonnes (MT), with India (4,470,000 MT), Myanmar (3,721,950 MT) and Brazil (3,435,370 MT) as the top three producing countries of dry bean (Food and Agriculture Organization 2013). These three countries account for almost 50% of world production. According to FAO STAT (2013), Canada is ranked as the 25th largest producer of dry bean in terms of global production. This ranking is down from being the 14th highest ranking country in terms of dry bean production in 2009. In 2011, Canada produced 144,660 MT (223,800 MT in 2010) of dry beans on 66, 400 ha (Anonymous 2009a; Food and Agriculture Organization 2013).

Dry beans are the largest traded pulse crop in the world by volume (tonnes) (Anonymous 2000b; McVicar 2009). In 2009, the top five dry bean exporting countries (in order of quantity exported in descending order) were China, Myanmar, United States of America, Argentina and Canada. These countries accounted for more than 75% of the world export (Food and Agriculture Organization 2013). In contrast, globally, dry bean imports are widely distributed among countries and the top 5 importing countries only account for approximately 33% of all imported dry beans. The top importing countries are India, Brazil, United States of America, the United Kingdom and Mexico (Food and Agriculture Organization 2013).

Canadian dry bean production has been variable in the past ten years and overall is trending upwards; however, production in Manitoba specifically has declined in recent years. In 2009, Canada produced 217,600 MT (Statistics Canada 2009). Of this, Ontario accounted for 38% of Canadian production, Manitoba accounted for 36% and Alberta accounted for 23%. Remaining production was in Quebec and Saskatchewan (Statistics Canada 2009).

2.1.4 Manitoba Dry Bean Production

Dry beans have been grown commercially in Manitoba since 1963 when the first 40 hectares were harvested. Since then the industry has grown at a respectable rate and by the 1990s production was at approximately 26,000 hectares. Acres continued to increase until 2002 when peak production was reached. Manitoba harvested 125,450 hectares of dry beans (Anonymous 2002) in 2002. Since 2002, production has been declining and in the past 5 years (2008-2012) average annual production has been about 57,000 hectares in Manitoba (Anonymous 2013a).

In Manitoba, the south central region of the province is best suited for dry bean production due to the growing conditions and soil type in this area (Anonymous 2001).

Dry beans have traditionally been grown in a wide row (row crop) production system in this area, however, another production option for producers is a narrow row (solid seeded) production system. This system is ideal for producers who have become accustomed to growing solid seeded crops like cereals, canola and flax, and are diversifying their operation by adding dry beans into their crop rotation (Anonymous 2006; Blackshaw et al. 2000; Blackshaw et al. 2007; Miller et al. 2000).

In a wide row production system, beans are grown in rows of 75 - 90 cm (Blackshaw et al. 1999; Schneiter and Nagle 1980; Teasdale and Frank 1983). This production system requires specialized equipment that can be set according to the exact width of the rows. Wide row beans are seeded with a row crop planter or a special bean planter. In wide row production, the individual plants grow in close proximity and therefore have to compete for water, nutrients and light (Malik et al. 1993; Teasdale and Frank 1983). The target plant population for dry beans in wide row production in southern Manitoba is 28 plants m^{-2} (Anonymous 2006). To achieve this plant population the seeding rate for pinto beans is 55 - 75 kg ha^{-1}.

Producers using narrow row dry bean production are typically practicing a solid seeded rotation (canola, cereals, flax). Dry beans can be introduced into a rotation with only minor modifications to existing operations and equipment. Solid seeded beans are planted in rows separated by 12.5 - 20 cm (Blackshaw et al. 2000; Malik et al. 1993; Teasdale and Frank 1983). Compared to wide row planted beans, a narrow row production system creates a more uniform distribution of plants, which leads to increased crop competition with weeds for light, nutrients and water. Plant populations are increased in narrow row production in order to take advantage of the decrease in competition between the plants (Anonymous 2006; Blackshaw et al. 2000; Malik et al. 1993; Schneiter and Nagle 1980; Teasdale and Frank 1983). The target population for dry beans in a narrow row production system should be approximately 48 plants m^{-2} (Blackshaw et al. 1999). To achieve this density, recommended seeding rates are 80 - 85 kg ha^{-1}. Solid seeded production is often the preferred system over a wide row dry bean production system due to the decreased labour and equipment costs (Blackshaw et al. 1999).

Weed control practices vary between the two production systems. Inter-row cultivation is the main practice for weed control in most wide row dry bean production systems. Cultivation can occur as many as three times within one growing season. A herbicide application in addition to inter-row cultivation is a highly effective option for weed control (Blackshaw et al. 2000; Burnside et al. 1994; Vangessel et al. 1998). The herbicide is applied in a band directly onto the individual bean rows. Herbicide costs with this type of precision application are greatly reduced because only about one third of the field is being sprayed (Anonymous 2006), however, overall costs with the combination of the cultivation and herbicide application are high (Blackshaw et al. 2000). Weed control in a narrow row production is typically accomplished solely by herbicide applications. Inter-row cultivation must be foregone in this production system; however, the increased plant population and smaller inter-row spaces provides the crop with increased competition between the bean plants and the weeds (Blackshaw et al. 1999; Malik et al. 1993; Teasdale and Frank 1983 Vangessel et al. 1998).

A major impediment in dry bean production is the limited options for in-crop herbicides (Anonymous 2006). There are currently only four commercial herbicides registered in Canada for in-crop application for dry beans; three that selectively control some grassy weeds (Select, active ingredient clethodim; Poast Ultra, active ingredient sethoxydim; Assure II, active ingredient quizalofop) and one that selectively controls broadleaf weeds (Basagran Forte, active ingredient bentazon). These products are only registered for control of a very limited spectrum of grassy and broadleaf weeds (Anonymous 2013).

Manitoba's climate and environmental conditions make it very well suited to bean production, due to the length of the growing season, moisture levels and soil type (Anonymous 2002). Although southern Manitoba is very well suited to dry bean production, it is not without its limitations. Manitoba, like much of the Great Northern plains, has a climate that is characterized by long cold winters, and short, but warm, summers. Precipitation, snowfall and spring time temperatures are variable and can be unpredictable (Miller et al. 2002). Snow covers the ground in southern Manitoba usually from November until March and accumulation typically ranges from 110 - 140 cm annually (Anonymous 2000a). The average frost free period in the dry bean producing areas of Manitoba is only approximately 100 - 130 days.

Another challenge in Manitoba dry bean production is frequent excess moisture in the spring. Annual precipitation in southern Manitoba is approximately 400 - 450 mm with the bulk of this precipitation occurring in the early summer months and September (Anonymous 2000a). These conditions of excess moisture often leave soils saturated and when these saturated soils are coupled with heavy snow cover in the winter there is potential for overland spring flooding. These unpredictable conditions can be challenging for crop production.

2.2 Desiccants

2.2.1 History

In modern agriculture, a desiccant is a herbicide used to hasten the maturation process of the crop at harvest. A desiccant can be classified as either a contact or a systemic herbicide. A contact herbicide will kill any plant surface with which it comes in contact and it is most effective against weeds with an annual life cycle. In order to have success with contact herbicides good coverage of the plant tissue is required (Ware and Whitacre 2004). Systemic herbicides are absorbed by the plant (either the above or below ground portion) and then translocated throughout the plant. Systemic herbicides control both annual and perennial weeds; however, they are particularly effective against established perennial weeds (Baumann 2008; Muzik and Mauldin 1976; Ware and Whitacre 2004). Ideal desiccants provide even crop desiccation (for increased harvest efficiency) and excellent late season weed control.

Herbicides have been used as desiccants since the late 1940s (Stahler 1953). The first desiccants were contact herbicides and were most often applied to potato, cotton, alfalfa, soybean or rice crops. The main priority of producers using desiccants at this time was drying down uneven crop stands to help with harvest efficiency (Stahler 1953). The first products used as agricultural desiccants were either a dust or a spray. In 1952, eight different products were commonly used for crop desiccation which included: calcium cyanamide, monosodium cyanamide, endothall, pentachlorophenol, potassium cyanate, sodium chlorate, sodium monochloroacetate and magnesium chlorate hexahydrate (Stahler 1953).

2.2.2 Current Use

Contact herbicides used for field crop desiccation include the active ingredients paraquat, diquat, carfentrazone-ethyl, flumioxazin, glufosinate and flumioxazin. Diquat (common name Reglone), carfentrazone-ethyl (Aim), flumioxazin (Valtera) and saflufenacil (Kixor) are currently the only active ingredients registered as desiccants in Manitoba (Anonymous 2013). Currently, these harvest aid products range in price from approximately \$2.00 ha^{-1} (saflufenacil) to \$7.50 ha^{-1} (diquat) (pers. comm. M. Murphy 2013). Paraquat and glufosinate ammonium (are not currently registered for pre-harvest use in Manitoba) have also been used for crop desiccation (Anonymous 2013).

2.2.2.1 Paraquat

In western Canada, paraquat is registered under the common name Gramoxone (Anonymous 2013). Gramoxone is a group 22 herbicide and is registered for use on stale seedbeds, inter-row weed control, control of weed seedlings in alfalfa and birdsfoot trefoil, non-selective weed control in shelterbelts and as a pre- or post-seeding burn down (Anonymous 2013).

Paraquat was one of the first herbicides to be registered as a crop desiccant (Sprague 2009) and is a fast acting, non-selective herbicide that desiccates plant tissue on contact (Dinham 1996; Reigart and Roberts 1999). In a recent study, Wilson and Smith (2002) found that paraquat caused injury symptoms on dry beans in as few as three days when applied as a crop desiccant. Paraquat also caused a reduction in yield (up to 22% yield loss) and poor seed quality. Experiments by Cerkauskas et al. (1982) also showed that paraquat application to dry beans prior to physiological maturity of the seed caused reductions in seed quality.

Paraquat was first discovered to have herbicidal properties in 1955 and globally, has become one of the most widely used herbicides. Prior to the introduction of glyphosate in 1974, paraquat held the largest share of the global herbicide market (Atkinson and Grossbard 1985). Market share and overall use of paraquat began to decline when concerns regarding the safety of the chemical arose.

Paraquat is known to be a highly toxic chemical and has been found to be poisonous to fish and mammals (Dinham 1996; Kervégant et al. 2013; Reigart and Roberts 1999). Toxic effects of this chemical can range from mild dermatitis to pulmonary edema to death (Dinham 1996; Kervégant et al. 2013; Reigart and Roberts 1999). Studies have indicated that ingestion of as little as one teaspoon (15 ml) of this chemical can be fatal in mammals (Dinham 1996; Kervégant et al. 2013; Reigart and Roberts 1999). Due to this high acute toxicity, paraquat is now considered a restricted-use pesticide in the United States (Gianessi and Marcelli 2000; Reigart and Roberts 1999) and has been a banned substance in Europe since 1997 (Kervégant et al. 2013).

2.2.2.2 Diquat

In western Canada, diquat is registered as the active ingredient of Reglone desiccant (Reigart and Roberts 1999; Senseman 2007). Reglone is a group 22 contact herbicide registered for the desiccation of immature crops and green weeds to facilitate harvest (Clark and Hurst 1970; Croshney 1961; Jones and Vale 2000). Diquat is very effective as a desiccant due to its ability to accelerate crop dry down with no negative effects on germination, emergence or seed quality (Anonymous 2010b; Sharma 1986; Zagonal 2011). This herbicide has no soil residual effects and once contact with the soil is made the diquat ions become inactivated due to strong bonding with the negative charged soil particles (Anonymous 2010b; Senseman 2007; Sharma 1986). There are no cropping restrictions for planting the year following a diquat application (Anonymous 2013). Ensuring adequate crop coverage with diquat is critical since the herbicide provides little to no systemic action or translocation (Retzlaff 2004; Zagonal 2011). From the prospective of producers, diquat is a relatively expensive pre-harvest treatment for crop desiccation especially if there are other options available (Anonymous 2013).

A number of toxicological concerns are associated with diquat. Diquat is highly toxic to mammals and can be fatal if swallowed (Anonymous 2010b; Jones and Vale 2000; Senseman 2007). While the effects of swallowing or inhalation can be fatal, symptoms and consequences can also be non-lethal. These non-lethal effects include damage to the liver, kidneys, lungs and gastrointestinal tract, and irritation of the skin. It has been shown that the effects of diquat poisoning are typically less damaging to mammals than paraquat poisoning (Jones and Vale 2000; Reigart and Roberts 1999).

2.2.2.3 Glufosinate Ammonium

Glufosinate ammonium is a group 10, non-selective, post-emergence contact herbicide used to control a broad spectrum of broadleaf and grassy weeds (Coetzer et al. 2001; Kumaratilake and Preston 2005; Mersey et al. 1990; Senseman 2007; Steckel et al. 1997) and is registered in Western Canada under the commercial name Liberty and Ignite SN and is most commonly used on genetically modified Liberty Link canola and glufosinate resistant corn or as a desiccant in dry bean production (Anonymous 2010a; Anonymous 2011b; Anonymous 2013; Senseman 2007). Glufosinate has been registered as a herbicide since the mid-1980s and has had different multiple uses since that time (Anonymous 1998; Kumaratilake and Preston 2005). Prior to use in genetically modified, glufosinate resistant cropping systems, glufosinate was used as a non-selective, fast acting, post-emergence herbicide in orchards, vineyards and as a crop desiccant (Coetzer et al. 2001; Mersey et al. 1990; Senseman 2007; Steckel et al. 1997).

Glufosinate contains all the characteristics of an excellent plant desiccant. Injury symptoms appear quickly on the plants, there is no residual activity in the soil due to rapid microbial breakdown (thus no cropping restrictions the year following application), and it offers a broad spectrum of post emergent weeds controlled with application (Anonymous 2010a; Coetzer et al. 2001; Mersey et al. 1990; Senseman 2007; Steckel 1997). When applying glufosinate, appropriate water volumes are required to ensure good coverage and penetration of the chemical into the crop canopy. In addition to water volume, the effectiveness of glufosinate is dependent on many environmental conditions. For example, the development of injury symptoms is promoted by a complex interaction between warm temperatures, high humidity and, to a lesser degree, increased sunlight (Coetzer et al. 2001; Mersey et al. 1990; Senseman 2007; Steckel 1997). Studies have shown that if these conditions are not met, weed control may be reduced (Coetzer et al. 2001; Kumaratilake and Preston 2005; Mersey et al. 1990; Steckel et al. 1997). For maximum efficacy hot, humid conditions are required at the time of application of glufosinate (Coetzer et al. 2001; Kumaratilake and Preston 2005).

2.2.2.4 Saflufenacil

Saflufenacil is a new active ingredient in the protoporphyrinogen oxidase (PPO) inhibiting class of herbicides (Group 14) and is registered under the brand name Kixor™ developed by BASF (Anonymous 2013; Grossman et al. 2010; Grossman et al. 2011). PPO inhibitors act on the enzyme that converts protoporphyrinogen to protoporphyrin. This inhibition leads to an accumulation of protoporphyrin in the plasmalemma which hinders chlorophyll and heme synthesis (Dayan et al 2010; Duke et al 1991; Grossman et al 2010). Released in 2010, saflufenacil is registered for use as a selective herbicide for use in pre- and post-seed applications, chemfallow and desiccation applications (Anonymous 2013; Grossman et al. 2011; Knezevic et al. 2009; Soltani et al. 2009).

Saflufenacil has many characteristics that make it an ideal desiccant. It provides both contact and systemic activity on the target plant species, with injury symptoms developing rapidly (within hours) and complete plant death within 1 – 3 days (Anonymous 2008; Knezvic et al. 2009; Soltani et al. 2009). The majority of the saflufenacil movement occurs within the xylem of the plant; however, saflufenacil has been found to exhibit some limited movement through the phloem (Ashigh and Hall 2010; Soltani at al 2009). This phloem movement is uncharacteristic of other PPO inhibitor herbicides that translocate entirely through the xylem. Similar to all other PPO inhibitors, saflufenacil does require adequate spray coverage to ensure complete tissue desiccation (Grossman et al. 2010, Grossman et al. 2011; Soltani et al. 2009). The new mode of action of saflufenacil is desirable due to its low use rate, apparent low environmental, toxicological and eco-toxicological impact and short persistence in the soil (Knezvic et al. 2009; Soltani et al. 2009).

2.2.2.5 Flumioxazin and Carfentrazone-ethyl

Flumioxazin and carfentrazone-ethyl are also group 14 PPO inhibiting contact herbicides used as pre-emergent and harvest aid herbicides in Manitoba (Anonymous 2013). Flumioxazin is registered in Manitoba under the commercial name Valtera and is only registered for application prior to soybean seeding and dry bean desiccation (Anonymous 2013). Carfentrazone-ethyl has a broader registration than flumioxazin in Manitoba and is registered for use prior to the seeding of nineteen different crop (including cereals, pulses, legumes and oil seeds) and as a harvest aid for nine different crops (including spring cereals, dry bean, chick pea, field pea, sorghum and potato) (Anonymous 2013).

2.3 Glyphosate

2.3.1 History of Glyphosate

The discovery of the active ingredient glyphosate was an important moment in the history of agriculture. The herbicidal activity of the glyphosate molecule (*N*-[phosphonomethyl]glycine) was discovered by Monsanto (previously Monsanto Agricultural Products Co.) scientist, Dr. John E. Franz, in 1971 (Atkinson and Grossbard 1985; Franz et al. 1997). Dr. Franz received the National Medal of Technology, the highest level of technical achievement, in 1987 for his work in discovering this molecule

(Anonymous 2005). Monsanto had been trying for years prior to 1970 to produce a herbicide that was specifically targeted at perennial weeds and had a systemic mode of action (Atkinson and Grossbard 1985). Roundup was the first glyphosate product introduced into the commercial herbicide market in Europe in 1974 by Monsanto (Atkinson and Grossbard 1985; Franz et al. 1997). The "Roundup" brand is a registered trademark of the Monsanto Company and since its introduction in the mid-1970s has grown to be the first herbicide in the agricultural industry to gross over a billion dollars in sales (Franz et al. 1997).

Glyphosate is a herbicide with unique biological properties. Glyphosate is a broad spectrum, systemic, non-selective, post-emergent herbicide that has shown to have high levels of activity on almost all annuals, biennials and perennials (Atkinson and Grossbard 1985; Baylis 2000; Franz et al. 1997; Hartzler et al. 2006; Sharma 1986). Glyphosate is known to effectively control 76 of the world's top 78 worst weeds (Atkinson and Grossbard 1985).

Due to the function of the glyphosate molecule within the plant it is has low mammalian toxicity. Once glyphosate has been introduced into the plant through leaf surfaces, it disrupts the enolpyruvyl-shikimate phosphate (EPSP) synthase enzyme. This enzyme is crucial for the production of aromatic amino acids that are essential for plant growth (Baylis 2000; Franz et al. 1997). The disruption of the EPSP synthase results in an accumulation of shikimate-3-phosphate and an overall reduction in protein synthesis.

This reduction in the plants ability to synthesize protein leads to an inhibition of photosynthesis and plant growth ceases (Baylis 2000; Franz et al. 1997). Symptoms begin to develop in plants within 5 to 10 days with full plant death occurring within 10 to 20 days after application (Cobb and Reade 2010; Sharma 1986). EPSP synthase is not present in mammals, which contributes to low mammalian toxicity of pure glyphosate (Cobb and Reade 2010; Franz et al. 1997).

Another property that makes glyphosate unique is its ability to rapidly degrade in the soil. Glyphosate binds tightly to soil particles making it unavailable to nearby plant roots. This rapid and tight binding means that there is low potential for leaching and minimal concerns for carryover or residual soil activity in most soils (Baylis 2000; Franz et al. 1997; Senseman 2007).

Glyphosate's herbicidal utility for broad spectrum weed control spans four different areas for application. These areas are: (i) use in cropland (either cropland in production or not in production), (ii) removal of vegetation in plantations, orchards or forestry, (iii) industrial and recreational use and (iv) use in residential capacities (Anonymous 2013; Atkinson and Grossbard 1985; Franz et al. 1997). Due to the limited solubility of the glyphosate acid in water, glyphosate products require formulation. These formulations include the glyphosate molecule, a soluble salt (most commonly isopropylamine (IPA) salt), water and a surfactant. The surfactant in the formulation assists in the adherence of the product to the plant leaf surface, which then allows the penetration of the glyphosate into the plant (Atkinson and Grossbard 1985; Baylis 2000; Cobb and Reade 2010; Hartzler 2006).

Glyphosate has played an integral role in the transition to and adoption of conventional tillage to reduced or conservation tillage. Without the availability of a weed control product with the ease and flexibility of glyphosate, producers would have had more difficulty transitioning to this new type of cropping system (Franz et al. 1997). Economically, glyphosate is a low cost to producers at approximately \$1.75 ha^{-1} (pers comm. M. Murphy 2013).

2.3.2 Current Use Patterns

2.3.2.1 Pre-Seed/Pre-Emergent Weed Control

Pre-seed or pre-emergent (PRE) weed control is done either prior to seeding or just after seeding but before the crop emerges. Glyphosate used as a PRE treatment targets annual weeds that emerge early in the spring or winter annuals or perennial weeds that have over-wintered from the previous fall. This treatment is ideal in cropping systems that practice reduced or conservation tillage. Producers must ensure that there are no crop plants emerging during a pre-emergent glyphosate application due to the potential sensitivity of the crop to the glyphosate. This is an important consideration when seeding large seeded crops like corn, soybeans and dry beans as any cracks or separation in the soil can lead to the glyphosate coming into contact with germinating seedlings (Anonymous 2013; Krausz et al. 1996).

2.3.2.2 In-Crop Weed Control

Glyphosate can be applied post-emergence in crops that are genetically engineered to be resistant to glyphosate. The most common glyphosate resistant crops are corn, soybean, canola and cotton (Devine 2005). The first glyphosate resistant crops were introduced in 1996 and since then the area planted to these transgenic plants have increased dramatically (Anonymous 2010c; Devine 2005). The glyphosate resistant cropping system allows producers to apply their herbicides as required, with few restrictions for time of application, making weed control more efficient (Franz et al. 1997) with minimal risk of crop injury. This system offers producers a flexible weed management system, even allowing more than one application of glyphosate if necessary (Clayton et al. 2002; Duke and Powles 2008; Reddy and Whiting 2000).

2.3.2.3 Pre-harvest Glyphosate Application

An application of glyphosate prior to harvest can assist in desiccation of the crop, promote even maturity of seed at harvest and also aid in perennial weed control (Baig et al. 2003; Ratnayake and Shaw 1992; Yenish and Young 2000). A pre-harvest application can create increased harvest efficiency and potentially reduce crop drying costs (Yenish and Young 2000). Producers using a glyphosate pre-harvest application must be aware of the risks involved if application is made when plants are not physiologically mature and the potential negative effect on seed quality (Azlin and McWhorter 1981; Ratnayake and Shaw 1992; Wilson and Smith 2002; Yenish and Young 2000). Risks associated with applications of herbicides prior to physiological maturity of the plant include reduced yield, seed germination and vigor the following planting year and unwanted residue accumulations in the seed (Azlin and McWhorter 1981; Baig et al. 2003; Ratnayake and Shaw 1992; Wilson and Smith 2002; Yenish and Young 2000).

2.3.3 Limitations and Concerns for Glyphosate

2.3.3.1 Chemical Limitations

Glyphosate is a herbicide with many obvious strengths and seemingly few weaknesses when compared to other herbicides; however, there are a few characteristics of glyphosate that are less than desirable. Glyphosate is relatively slow acting and slow to develop symptoms once it has been applied (Baylis 2000; Cobb and Reade 2010; Hartzler et al. 2006; Sharma 1986). On average, it usually takes 7 to 10 days for symptoms to develop and can vary depending on environmental conditions at time of application (Baylis 2000; Cobb and Reade 2010; Hartzler et al. 2006; Sharma 1986).

Water quality is an important consideration when mixing glyphosate for application. For example, the use of hard water can affect the effectiveness of the chemical and overall weed control due to the level of dissolved salts found in the water (Buhler and Burnside 1983; Hartzler et al. 2006; Jordan et al. 1997; Krausz et al. 1996; Thelen 1995). There is also the potential for antagonism when mixing glyphosate with some tank mix partners (Baylis 2000; Hydrick and Shaw 1994; Lich et al. 1997; Selleck and Baird 1981). Finally, one of the more notable weaknesses of glyphosate is the potential need for a higher dose of application required in some instances. On occasion, higher than normal rates can be required for harder to-kill weeds or for weeds that are more tolerant to the glyphosate molecule. Adequate foliar coverage is important in any attempt to control these weed species (Ashigh and Hall 2010; Baylis 2000; Duke et al. 2003; Shaw and Arnold 2002).

2.3.3.2 Potential Environmental Impact and Toxicity to Non-Target Organisms

Concerns surrounding the safety and the environmental impact of glyphosate have been increasing in the more than 30 years that glyphosate has been widely used. Studies have provided conflicting information about the overall safety and toxicity of glyphosate use and the inherent risk to the environment and animals. Reviews by Williams et al. (2000), Cerdeira and Duke (2006), Borggard and Gimsing (2008) and Wagner et al. (2013) have provided great detail surrounding the current concerns regarding environmental fate and impact of glyphosate, the overall safety of glyphosate (the molecule and the formulated product) for humans and other mammals and the potential impact of glyphosate on amphibians.

The unformulated glyphosate molecule is considered to have a low apparent impact on the environment; however, several formulated glyphosate products have been found to be more toxic to aquatic organisms, amphibians in particular (Howe et al 2004; Wagner et al 2013). Research by Howe et al (2004) summarized that the glyphosate molecule alone (non-formulated) resulted in no toxic effects to amphibian populations, while populations exposed to formulated glyphosate products demonstrated side effects ranging from development abnormalities to death. Both formulated glyphosate products and the glyphosate molecule alone have been extensively investigated for potential health risks to humans and it has been concluded that the apparent risk of acute or chronic toxicity is low (Williams et al 2000).

Glyphosate has an environmental half life of approximately 45-175 days due to microbial degradation in the soil (Borggaard and Gimsing 2008; Cerdeira and Duke 2010). Despite this, and the binding ability of glyphosate to soil particles, there is still potential for glyphosate to leach through soils into surface and ground waters (Cerdiera and Duke 2006, Borggaard and Gimsing 2008; Gerdiera and Duke 2010). Coarse, structured soils containing macropores and pronounced preferential flow are at the greatest risk for glyphosate leaching into surface and ground waters (Cerdiera and Duke 2006, Borggaard and Gimsing 2008; Gerdiera and Duke 2010). A consideration for the environmental impact for glyphosate is that in most cases, glyphosate based products are often preferable in terms of environmental and toxicological impact when compared to alternative herbicides (Howe et al. 2004; Cerdeira and Duke 2006; Wagner et al 2013).

2.3.3.3 Residue Accumulation in Seed

One of the largest concerns surrounding the use of glyphosate as a harvest aid is that the improper application of this herbicide treatment can lead to an accumulation of residues in the harvested seed. The appropriate time of application for glyphosate pre-harvest is following physiological maturity of the bean seed (Cessna et al. 2002; Wilson and Smith

2002). Physiological maturity of dry beans is 80% PCC (equal to about 30% seed moisture content), when maximum dry matter accumulation has been achieved (Cessna et al. 2002; Fageria and Santos 2008; Wilson and Smith 2002). When pre-harvest applications are made prior to maturity, glyphosate and its metabolite, aminomethylphosphonic acid (AMPA), have the potential to accumulate in the immature embryo and endosperm of the crop seed (Baig et al. 2003; Cessna et al. 2000; Cessna et al. 2002). Cessna et al. (2000; 2002) determined that the rate of application of glyphosate and the stage of development of the crop affected the overall accumulation of glyphosate residue in the seed. The appropriate time of application of the glyphosate can circumvent the accumulation of unwanted residues (Cessna et al. 2000; Cessna et al. 2002).

The level of glyphosate that translocates into the seed appears to be dependent on various factors. The rate of glyphosate applied, the physiological maturity (stage of crop development) of the crop and the environmental conditions at the time of application all seem to play a considerable role with respect to the degree of translocation of the glyphosate and AMPA into the seed (Cessna et al. 2000; Cessna et al. 2002). In studies conducted by Cessna et al. (2000; 2002) glyphosate residue levels in the seeds of different crops (pea, barley, flax and canola) increased as the level of glyphosate applied increased. In Cessna et al. (2002) for example, in field pea, glyphosate residue increased from 0.56 mg kg^{-1} at the most mature stage of the pea crop to 16.44 mg kg^{-1} at the least mature stage of the pea crop, at the lowest rate of glyphosate applied.

2.3.3.4 Effect of Glyphosate on Seed Yield and Quality

Most glyphosate labels recommend that glyphosate not be used as a pre-harvest treatment if the crop is intended for seed production for the following crop season (Anonymous 2013). A glyphosate application has the potential to affect the quality of the seed through a reduction in germination, vigor and yield (Ratnayake and Shaw 1992; Wilson and Smith 2002; Yenish and Young 2000). This risk is increased if the application is made outside of the recommended stage of crop development for pre-harvest treatments (Baig et al. 2003; Ratnayake and Shaw 1992; Wilson and Smith 2002; Yenish and Young 2000).

2.3.3.5 Maximum Residue Limits

There have been global standards developed to monitor and regulate the concentration of pesticide residues in harvested products. These established standards are known as maximum residue limits (MRLs) (Food and Health Organization 2010; Foreign Agricultural Service 2012; Granby et al. 2003). Different nations have differing sensitivities for allowable MRL for different herbicides in harvested products. Table 2.1 has been adapted from the International Maximum Residue Limit Database and illustrates the differences in MRL tolerances in dry beans (Pinto) for carfentrazone-ethyl, diquat, flumioxazin, glufosinate, glyphosate and saflufenacil in the European Union, Codex Alimentarius, (International Food Standards), Japan, the United States and Canada.

Table 2.1 Maximum Residue Limits (MRL) in parts per million (ppm) in dry bean (Pinto) for Codex Alimentarius (International Food Standards), Canada, European Union (EU), Japan and the United States (US). Adapted from the International Maximum Limit Database (Foreign Agricultural Service 2012).

	Established MRL (ppm)				
Herbicide	Codex	Canada	EU	Japan	US
Carfentrazone-ethyl	-*	0.10	-	0.10	0.10
Diquat	0.20	0.20	-	0.20	0.05
Flumioxazin	-	0.05	-	0.10	0.07
Glyphosate	2.00	4.00	2.00	2.00	5.00
Glufosinate	2.00	-	-	-	-
Saflufenacil	0.30	0.30	-	0.30	0.30

*--(dashes indicate that no specific MRL for the commodity or relevant crop group is established

2.4 Research Objectives

This research was designed to investigate 3 objectives. These were:

i. To determine if tank-mixing various contact herbicides with glyphosate will reduce translocation of glyphosate into dry bean seed (mixture applied at recommended dose and growth stage).

ii. To determine if the application of glyphosate, saflufenacil and a glyphosate/saflufenacil tank-mix at various stages of maturation has an effect on residue accumulation in the seed.

iii. To establish whether a reduced rate of glyphosate mixed with various contact herbicides will have a comparable efficacy of weed control as a full rate of glyphosate.

3.0 EVALUATION OF TANKMIXING CONTACT HERBICIDES WITH GLYPHOSATE AT PREHARVEST TIMING ON THE ACCUMULATION OF RESIDUES IN DRY BEAN SEED

Abstract. Field experiments were conducted in 2010 and 2011 to determine the effect of different harvest aid herbicides and their tank-mixes with glyphosate on dry bean desiccation, yield, seed quality and glyphosate residue accumulation in the seed. . At physiological maturity, windbreaker pinto beans were treated with carfentrazone-ethyl, diquat, flumioxazin, glufosinate and saflufenacil alone or in mixture with glyphosate. Treatments containing carfentrazone-ethyl provided the poorest desiccation and overall efficacy of all herbicide treatments. Final yield and seed quality was not affected when harvest aids were applied at physiological maturity of bean plants. In 2010, there were no significant differences in glyphosate residue levels in seed among any treatments containing glyphosate while in 2011 several treatments containing contact herbicides reduced the level of glyphosate accumulation relative to glyphosate alone. These results indicate that the addition of diquat, flumioxazin, glufosinate and saflufenacil appear to improve the overall efficacy of glyphosate alone and reduce the risk of glyphosate accumulating in the harvested bean seed.

3.1 Introduction

Dry beans often exhibit an indeterminate growth habit and frequently this growth habit and spatial variability can result in uneven maturation within a field. To alleviate uneven maturation, growers generally use a broad spectrum herbicide to assist harvest by desiccating the bean plants and providing late season weed control (Anonymous 2006). Herbicides currently registered and used by producers for application to dry bean shortly before harvest are glyphosate (multiple trade names, including: Roundup™), carfentrazone-ethyl (Aim™), glufosinate ammonium (Ignite™) and diquat (Reglone™) (Anonymous 2013). Recommended application time of harvest aid herbicides is when 80% of the bean pods have begun to change colour. This colour change signifies that the bean plant has reached physiological maturity (accumulation of dry matter in the seed has finished) (Wilson and Smith 2002). Application timing of a harvest aid herbicide is critical as it may affect final yield or result in unacceptable levels of herbicide residue in the seed (Cessna et al. 2000; Cessna et al. 2002).

Glyphosate is the most common harvest aid herbicide used by producers in dry bean production in Canada (Atkinson and Grossbard 1985; Sharma 1986). Glyphosate provides a uniform dry down of the beans, excellent weed control and controls bean regrowth (Atkinson and Grossbard 1985; Baylis 2000; Hartzler et al. 20061021; Sharma 1986).

When glyphosate is applied to the dry bean plant, it translocates throughout the plant and causes mortality. If this application is made at an immature stage of development, glyphosate will still move systemically throughout the plant but there is a greater risk that glyphosate will translocate into the seed and accumulate, leaving glyphosate residue in the harvested bean seed. Glyphosate residue in the seed can be problematic if residue levels are detected above internationally accepted maximum residue limits (Food and Health Organization 2010; Foreign Agricultural Services 2012) since some export markets will not accept harvested products that contain these unacceptable residues.

Glyphosate use restrictions are becoming stricter as a result of an incident in 2008 where a shipment of Canadian dry beans was rejected by Japan due to the detection of glyphosate residues above the maximum accepted level of 2 parts per million (Sprague 2009). Other registered harvest aids are contact herbicides that often provide inadequate control of difficult to control annual, winter annual and perennial weeds at harvest time. These herbicides are often considerably more expensive then glyphosate (Anonymous 2013) often making them undesirable to producers. New harvest aid options for producers are required as alternatives to glyphosate. There are new chemicals currently available in the market that have the potential to act as desirable harvest aid herbicides but are not registered for pre harvest application use.

The objective of this study was to evaluate new and existing harvest aid herbicides for use in Manitoba dry bean production to determine if they are capable of providing desiccation of bean plants while reducing residues of glyphosate and its metabolite AMPA from seed.

3.2 Methods and Materials

3.2.1 Site Establishment

Field experiments were conducted in 2010 and 2011. In both years, field experiments were established at the University of Manitoba Ian N. Morrison Research Farm (49° 30’ 5.80” N 98° 01’ 39.75 W) in Carman, Manitoba. Soil samples were taken at the 0 – 15 cm and 15 – 60 cm depths in the fall of 2009 and spring of 2011 to determine nutrient availability and requirements. One day prior to seeding, nitrogen (46-0-0) and phosphorous (11-52-0) fertilizers were broadcasted at rates of 78 kg ha^{-1} and 22 kg ha^{-1}, respectively and incorporated immediately to a depth of 5 cm using cultivation in both years.

3.2.2 Experimental Design

This experiment was structured in a randomized complete block design (RCBD) with four replicates. A one way treatment structure was used with the application of harvest aids serving as treatments. Each block contained a total of 24 treatments consisting of 23 different herbicide treatments plus an untreated control.

3.2.3 Dry Bean Establishment

The dry bean cultivar “Windbreaker” was chosen for these studies based on the Manitoba Seed Guide and the cultivar’s current use in Manitoba. In 2010 and 2011, seed was acquired from Agassiz Seed Farm in Homewood, Manitoba and from Legumex in Plum Coulee, Manitoba, respectively. Prior to planting, all seed was treated with the recommended dose of Apron Maxx

RTA (active ingredient fludioxonil, 0.73%; metalaxyl-M, 1.10%) (Anonymous 2013), a common seed treatment used in dry bean production to prevent certain seed and soil borne diseases. Bean seed was planted at 83 kg ha^{-1} and a row spacing of 75 cm on June 9th, 2010 and June 18th, 2011, using a small plot seeder. Seed was placed at a depth of 2.5 – 3 cm.

3.2.4 In-Crop Weed Control

In 2010, a non-selective herbicide was applied prior to crop emergence. Roundup Weathermax (active ingredient glyphosate, 540 g L^{-1}) (Anonymous 2013) was applied at a dose of 3.75 L ha^{-1} with a water volume of 100 L ha^{-1}. This pre-emergence application of herbicide was conducted on June 14. Basagran Forte (active ingredient bentazon 480 g L^{-1}) (Anonymous 2013) was applied at a dose of 2.275 L ha^{-1} at a carrier (water) volume of 100 L ha^{-1} on July 16 when the crop was at the 4th trifoliate developmental stage. Once bean plants had entered the reproductive stage of development, plots were hand weeded for the duration of the growing season to maintain weed-free conditions.

In 2011, a grass herbicide and a broadleaf herbicide were applied to the crop at the 2nd trifoliate developmental stage. Select (active ingredient clethodim, 240 g L^{-1}) (Anonymous 2013) and Amigo adjuvant were applied on June 28 at a dose of 0.2125 L ha^{-1} and 0.5% v/v, respectively. Basagran Forte was applied on June 30 at a rate of 2.275 L ha^{-1}. Both applications were made using a carrier (water) volume of 100 L ha^{-1}. Basagran Forte was applied a second time on July 7 at a dose of 2.275 L ha^{-1}, carrier (water) volume 100 L ha^{-1}, when the crop was at the 4th trifoliate developmental stage. As in 2010, plots were hand weeded once the bean crop had reached reproductive stage of development.

3.2.5 Harvest Aid Application

Harvest aid herbicide treatments were applied at physiological maturity (~80% PCC) of the bean seed (Cessna et al. 2002; Schwartz et al. 2004; Wilson and Smith 2002). Herbicide treatments were chosen based on current labelled dose rates. Most products have a range doses for application and in these cases the contact herbicide was used at the low, the high, and when necessary, at other common use rates. Each herbicide was applied alone and in mixture with glyphosate (Table 3.1). Where required, the recommended adjuvant was also included in the mixture. With the inclusion of an untreated control treatment, this resulted in a total of 24 harvest aid herbicide treatments.

Application of harvest aid herbicides occurred on September 13, 2010 (temperature 13°C, relative humidity 64%, wind NNW 13 km hr^{-1}) and August 30, 2011 (temperature 18°C, relative humidity 88%, wind SSE 5 km hr^{-1}). All harvest aid herbicides were applied using a compressed air pressurized backpack sprayer with a 1.5 metre handheld boom (4 Teejet 8003VS nozzles, 40 psi, 50 cm spacing). A water volume of 200L ha^{-1} is the recommended water carrier for diquat and this volume was used for all treatments.

Table 3.1 Harvest aid herbicide treatments applied at physiological maturity (80% pod colour change) of dry bean

Harvest Aid Herbicide	Rate	Adjuvant
Untreated Check		
Glyphosate (Weathermax)	900 g ai/ha	
Diquat (Reglone)	300 g ai/ha	AgSurf (0.1% v/v)
Diquat (Reglone)	400 g ai/ha	AgSurf (0.1% v/v)
Diquat (Reglone)	550 g ai/ha	AgSurf (0.1% v/v)
Glufosinate ammonium (Ignite)	370 g ai/ha	
Glufosinate ammonium (Ignite)	450 g ai/ha	
Carfentrazone-ethyl (Aim)	17.5 g ai/ha	AgSurf (0.25% v/v)
Carfentrazone-ethyl (Aim)	28 g ai/ha	AgSurf (0.25% v/v)
Flumioxazin (Valtera)	53.6 g ai/ha	MSO 2.5 L/ha
Flumioxazin (Valtera)	71.4 g ai/ha	MSO 2.5 L/ha
Saflufenacil (Kixor)	25 g ai/ha	Merge (0.5% v/v)
Saflufenacil (Kixor)	50 g ai/ha	Merge (0.5% v/v)
Glyphosate (Weathermax) Diquat (Reglone)	900 g ai/ha 300 g ai/ha	 AgSurf (0.1% v/v)
Glyphosate (Weathermax) Diquat (Reglone)	900 g ai/ha 400 g ai/ha	 AgSurf (0.1% v/v)
Glyphosate (Weathermax) Diquat (Reglone)	900 g ai/ha 550 g ai/ha	 AgSurf (0.1% v/v)
Glyphosate (Weathermax) Glufosinate ammonium (Ignite)	900 g ai/ha 370 g ai/ha	
Glyphosate (Weathermax) Glufosinate ammonium (Ignite)	900 g ai/ha 450 g ai/ha	
Glyphosate (Weathermax) Carfentrazone-ethyl (Aim)	900 g ai/ha 17.5 g ai/ha	 AgSurf (0.25% v/v)
Glyphosate (Weathermax) Carfentrazone-ethyl (Aim)	900 g ai/ha 28 g ai/ha	 AgSurf (0.25% v/v)
Glyphosate (Weathermax) Flumioxazin (Valtera)	900 g ai/ha 53.6 g ai/ha	 MSO 2.5 L/ha
Glyphosate (Weathermax) Flumioxazin (Valtera)	900 g ai/ha 71.4 g ai/ha	 MSO 2.5 L/ha
Glyphosate (Weathermax) Saflufenacil (Kixor)	900 g ai/ha 25 g ai/ha	 Merge (0.5% v/v)
Glyphosate (Weathermax) Saflufenacil (Kixor)	900 g ai/ha 50 g ai/ha	 Merge (0.5% v/v)

3.2.6 Measurements

3.2.6.1 Desiccation Ratings

Visual ratings of the desiccation of the leaves, stems and pods of the Pinto bean plants were conducted at 4, 8, 12 and 16 days after application of the harvest aid herbicide treatments. Crop desiccation was assessed by percentage plant tissue desiccated to a maximum of 99%, with 99% equal to complete desiccation. These ratings were used to determine speed of desiccation through the use of area under the desiccation progress curve calculations adopted from Wilcoxson et al. (1975).

3.2.6.2 Bean Yield

In 2010 and 2011, dry beans were harvested when the seeds were considered dry (seed moisture <18%) (pers. comm. C. Gillard, 2010). In each plot, the middle two rows were harvested using a Kincaid plot combine (8XP Kincaid; Kincaid Equipment Manufacturing; Haven, KS USA). Combine settings operated at a cylinder speed of 400 rpm, wind speed of 1000 rpm, sieves set at 1.5 cm and concave opening of 34. Harvest samples were bagged labelled and weighed immediately following threshing. Subsamples were collected from harvest samples, weighed and then dried in a drying oven. These subsamples were dried for 72 hours at 65°C and then reweighed. Gravimetric moisture content was determined at this time for each experimental unit (plot). Final yield was determined by using the harvest weights, plot size and then adjusting the yield to account for differences in moisture content. Yield was adjusted to a standard bean moisture content of 18%.

3.2.6.3 Seed Size and Thousand Kernel Weight

Pinto bean seed size was determined for each treatment for each site-year using image analysis software, Assess 2.0 (The American Phytological Society 2008) and a standard flatbed scanner (model CanoScan 5600F). A subsample of 75-100 Pinto bean seeds from each harvest sample was placed on the scanner and seed number and total seed area were determined using the Assess 2.0 software. From these, average individual seed size (cm^2) was determined by taking the total seed area and dividing this area by the number of seeds counted by the scanner. The seeds also were weighed and thousand kernel weight was determined by taking the weight of the sample and dividing the total weight by the number of seeds, then multiplying by one-thousand.

3.2.6.4 Harvest Aid Residue Accumulation

Subsamples (75 grams of seed) from all treatments were frozen and shipped to ALS Group Laboratory Testing in Edmonton, Alberta, Canada for determination of herbicide residue levels. For residue analysis, samples were frozen at -20°C and seed was finely ground. The residue analysis for glyphosate was conducted using High Performance Liquid Chromatography (HPLC) with Post-Column Derivitization and Fluorescence detection (pers. comm. B. Finnestad, 2011). Ground seed samples were prepared for analysis by the addition of a mixture of mild hydrocholoric acid and dichloromethane mixture. This solution was then mixed to homogenize and centrifuged. The aqueous solution was then decanted, diluted and loaded onto a Chelex 100 Fe III cation exchange column. This cation exchange column was then rinsed with a basic solution to remove any traces of acid then eluted with strong hydrochloric acid. An

AG1-X8 resin column was then used to remove excess iron from the resulting eluent and the subsequent extract reduced in volume using a rotary evaporator. The final extract was injected into the HPLC where the glyphosate and AMPA residues were separated chromatographically. Once separated, the extract from glyphosate and AMPA was treated to modify the molecules into fluorescing forms. The unique retention time of each herbicide relative to the calibration standards used to differentiate among glyphosate, AMPA and ambient (baseline) signals. The resulting information was compared to a calibration curve, and the concentration in each sample was determined using the calibration response and the extraction data (Archer and Stokkes 1984; pers. comm. B. Finnestad, 2011). The detection limit of the residue for this test is 0.020 mg kg^{-1}. This analysis was similar to glyphosate residue analysis work conducted by Ofitserova et al. (2011) of Pickering Laboratories, Inc.

3.2.6.5 Statistical Analysis

The speed of desiccation of Pinto bean plants was determined for each plant part using the area under the desiccation progress curve (AUDPC). The formula used to calculate AUDPC is:

$$AUDPC = \sum_{i=1}^{k} \frac{1}{2} (d_i + d_{i-1})$$

where d_i = percentage of variable (leaf, stem, pod) desiccated at each rating day i; k = number of rating days (Wilcoxson et al. 1975). The AUDPC was used to condense the data sets for each treatment and improve normality of the residuals.

Treatment effects were tested using analysis of variance (ANOVA). Normality of residuals was examined for the following response variables: Pinto bean leaf, stem and pod desiccation (using the AUDPC calculated values), yield, seed moisture content, seed size, thousand kernel weight and the residue analysis of glyphosate in the seed. The Univariate procedure (SAS Institute 2008) was used to test the assumptions of ANOVA and to determine whether the residuals conformed to the normal (Gaussian) distribution. Studentized residuals were used to determine outliers (Lund 1975). Outliers were removed using Lund's test at a Type 1 error rate = 0.05. The model was corrected for heterogeneity of treatment variances as necessary using the repeated / group option. The Mixed procedure was used with the correct model and means were separated using Fisher's protected LSD (<0.05) and the pdmix800 macro (Saxton 1998) using herbicide as the fixed effect and replicate as the random effect. Due to presumably high levels of interactions between site-years, data for each site-year was analyzed separately.

When the residuals of some response variables (seed moisture content and glyphosate residue analysis) did not conform to the normal distribution after transformation, a different approach for statistical treatment of these data was employed. In these cases, the GLIMMIX procedure (SAS Institute 2008) was used. For each affected response variable, the binomial, negative binomial and poisson error distributions were tested and the most appropriate error distribution based on the chi-square test result for overdispersion was used. When necessary the model was corrected for overdispersion.

3.3 Results

3.3.1 Efficacy and Speed of Desiccation

The visual ratings and area under the desiccation progress curve (AUDPC) were used to determine the speed and efficacy of each harvest aid herbicide on three different organs of the Pinto bean plant. The organs investigated were the stems, leaves and pods. For treatments for which the degree of final desiccation was not significantly different, differences in the AUDPCs among the treatments are indicative of the speed of desiccation. When desiccation of the target organs differed among treatments at the final time of rating, differences in the AUDPC may have been due to differences in final desiccation rating, differences in the speed of desiccation, or both. The differences in final desiccation rating were only statistically significant for bean leaves in 2010.

3.3.1.1 Diquat

In 2010, the addition of glyphosate to diquat did not improve the speed or efficacy of desiccation for any of the plant organs investigated (Table 3.2). All treatments containing diquat fully desiccated the stem, leaf and pod of the Pinto bean plants at a similar speed of desiccation. Similar to 2010, the addition of glyphosate did not improve the speed of desiccation of any organ in 2011 (Table 3.3); however, increasing the dose of diquat (alone or in mixture with glyphosate) from diquat300 to diquat550 improved the speed of desiccation in 2011.

3.3.1.2 Glufosinate

Speed and efficacy of desiccation provided by glufosinate was consistent in both site years (Table 3.2; Table 3.3). There were no differences among speed or efficacy of desiccation by glufosinate alone of in mixture with glyphosate for any plant part over the 16 day evaluation period.

3.3.1.3 Carfentrazone-ethyl

In 2010, the addition of glyphosate to carfentrazone-ethyl significantly improved the speed of desiccation for the stem and pod and speed and efficacy of leaf desiccation (Table 3.2). For stem and pod desiccation, Carfentrazone28/900 was the only treatment where the addition of glyphosate did not improve the speed of desiccation compared to carfentrazone alone at either dose. Carfentrazone28 did not exhibit full leaf desiccation in 2010, however, the addition of glyphosate to this treatment did improve final efficacy. Similar to 2010, the addition of glyphosate to carfentrazone-ethyl significantly improved the speed of desiccation for stems and pods in 2011 (Table 3.3). For leaf desiccation in 2011, only carfentrazone28/900 exhibited an increased speed of desiccation compared to the carfentrazone-ethyl alone treatments.

3.3.1.4 Flumioxazin

In 2010, the addition of glyphosate to flumioxazin71.4 improved the speed of desiccation compared to flumioxazin53.6 for all three plant organs (Table 3.2). In 2011, increasing the dose of flumioxazin alone and the addition of glyphosate to both doses improved the speed of desiccation for all plant organs (Table 3.3). All other treatments exhibited a similar speed of desiccation.

3.3.1.5 Saflufenacil

In 2010, the addition of glyphosate to saflufenacil did not improve the efficacy of desiccation for any of the organs investigated but did improve the speed of desiccation for leaf and pod (Table 3.2). The speed of desiccation of the leaf and pod was reduced when treated with saflufenacil50 compared to the saflufenacil25/900 and saflufenacil 25 treatments (leaf only). In 2011, the addition of glyphosate to saflufenacil25 improved the speed of desiccation for stems and pods (Table 3.3). All other treatments exhibited a similar speed of desiccation.

3.3.1.6 Alternative Harvest Aid Herbicides Applied Alone in Comparison to Diquat

The efficacy of harvest aid herbicides applied alone had variable effects on the desiccation of Pinto bean stems, leaves and pods when compared to a standard harvest aid herbicide, diquat. Three doses of diquat alone were compared to high and low doses of four potential alternative harvest aid herbicides (carfentrazone-ethyl, flumioxazin, glufosinate and saflufenacil) applied alone.

Table 3.2 Area under the desiccation progress curve (AUDPC) and desiccation (% Des.) of stems, leaves and pods at 16 days after application of harvest aid herbicides on Pinto bean in 2010

	Stem		Leaf		Pod	
Treatment (g ai ha^{-1})	AUDPC	% Des.	AUDPC	% Des.	AUDPC	% Des.
Glyphosate 900	223 *D-G* [a]	99	253 *DE*	99 *	233 *DE*	93
Diquat 300	215 *E-G*	98	261 *B-D*	98 *A*	238 *C-D*	91
Diquat 400	225 *C-G*	98	268 *A-D*	98 *A*	247 *A-D*	94
Diquat 550	247 *A-E*	99	271 *A-D*	99 *A*	266 *A-D*	98
Diquat 300/Glyphosate 900	220 *D-G*	97	255 *DE*	97 *A*	233 *DE*	91
Diquat 400/Glyphosate 900	237 *A-F*	99	271 *A-D*	99 *A*	255 *A-D*	93
Diquat 550/Glyphosate 900	245 *A-E*	91	270 *A-D*	97 *A*	249 *A-D*	91
Glufosinate 370	256 *A-D*	99	275 *A-D*	99 *	264 *A-D*	99
Glufosinate 450	267 *A*	99	290 *A*	99 *A*	278 *AB*	98
Glufosinate 370/Glyphosate 900	246 *A-E*	99	276 *A-D*	99 *A*	255 *A-D*	96
Glufosinate 450/Glyphosate 900	252 *A-E*	99	283 *A-C*	99 *	267 *A-D*	99
Carfentrazone-ethyl 17.5	201 *FG*	94	223 *F*	96 *A*	204 *EF*	84
Carfentrazone-ethyl 28	191 *G*	92	231 *EF*	92 *B*	193 *F*	79
Carfentrazone 17.5/Glyphosate 900	246 *A-E*	98	269 *A-D*	98 *A*	249 *A-D*	93
Carfentrazone 28/Glyphosate 900	227 *B-G*	97	263 *A-D*	97 *A*	234 *DE*	90
Flumioxazin 53.6	218 *D-G*	97	255 *DE*	99 *A*	230 *D-F*	88
Flumioxazin 71.4	256 *A-D*	99	273 *A-D*	99 *	256 *A-D*	97
Flumioxazin 53.6/Glyphosate 900	238 *A-F*	98	267 *A-D*	98 *A*	244 *A-D*	94
Flumioxazin 71.4/Glyphosate 900	263 *A-C*	99	284 *AB*	99 *	273 *A-C*	99
Saflufenacil 25	266 *AB*	99	285 *AB*	99 *	273 *A-C*	99
Saflufenacil 50	232 *A-F*	96	257 *CE*	99 *A*	241 *B-D*	89
Saflufenacil 25/Glyphosate 900	267 *A*	99	289 *A*	99 *	280 *A*	99
Saflufenacil 50/Glyphosate 900	256 *A-D*	99	272 *A-D*	99 *	266 *A-D*	99

[a]Within columns, means followed by the same letter are not significantly different according to Fisher's protected LSD at the 0.05 level of significance. If there is no letter present, means are not significantly different.
*indicates treatments with final mean ratings of 99% desiccation were not included in statistical analysis due to a lack of variation among the replicates

Table 3.3 Area under the desiccation progress curve (AUDPC) and desiccation (% Des.) of stems, leaves and pods at 16 days after application of harvest aid herbicides on Pinto bean in 2011

	Stem		Leaf		Pod	
Treatment (g ai ha^{-1})	AUDPC	% Des.	AUDPC	% Des.	AUDPC	% Des.
Glyphosate 900	244 *F*[a]	99	261 *F*	99	246 *E*	99
Diquat 300	259 *B-E*	99	276 *A-D*	99	264 *A-D*	99
Diquat 400	268 *A-D*	99	282 *A-C*	99	271 *AB*	99
Diquat 550	273 *A*	99	286 *A*	99	275 *A*	99
Diquat 300/Glyphosate 900	253 *EF*	99	271 *C-F*	99	255 *DE*	99
Diquat 400/Glyphosate 900	264 *A-E*	99	279 *A-C*	99	268 *A-C*	99
Diquat 550/Glyphosate 900	271 *AB*	99	284 *AB*	99	276 *A*	99
Glufosinate 370	266 *A-D*	99	274 *B-E*	99	266 *A-D*	99
Glufosinate 450	264 *A-E*	99	273 *B-E*	99	265 *A-D*	99
Glufosinate 370/Glyphosate 900	268 *A-D*	98	278 *A-C*	99	270 *A-C*	98
Glufosinate 450/Glyphosate 900	267 *A-D*	99	277 *A-D*	99	270 *AB*	99
Carfentrazone-ethyl 17.5	245 *F*	99	265 *D-F*	99	250 *E*	99
Carfentrazone-ethyl 28	252 *EF*	99	264 *EF*	99	255 *DE*	99
Carfentrazone 17.5/Glyphosate 900	259 *C-E*	99	272 *B-E*	99	262 *B-D*	99
Carfentrazone 28/Glyphosate 900	270 *A-C*	99	281 *A-C*	99	272 *AB*	99
Flumioxazin 53.6	255 *D-F*	98	273 *B-E*	99	258 *C-E*	99
Flumioxazin 71.4	269 *A-C*	98	277 *A-D*	99	274 *AB*	99
Flumioxazin 53.6/Glyphosate 900	274 *A*	99	281 *A-C*	99	274 *A*	99
Flumioxazin 71.4/Glyphosate 900	274 *A*	99	279 *A-C*	99	274 *AB*	99
Saflufenacil 25	259 *C-E*	99	271 *C-F*	99	264 *A-D*	99
Saflufenacil 50	270 *A-C*	99	280 *A-C*	99	273 *AB*	99
Saflufenacil 25/Glyphosate 900	274 *A*	99	278 *A-C*	99	274 *A*	99
Saflufenacil 50/Glyphosate 900	271 *A-C*	99	276 *A-D*	99	269 *AB*	99

[a]Within columns, means followed by the same letter are not significantly different according to Fisher's protected LSD at the 0.05 level of significance. If there is no letter present, means are not significantly different.

Stem desiccation. Speed of desiccation with diquat300 was similar to carfentrazone28, flumioxazin53 and saflufenacil50 in both site-years. The only treatment that exhibited lower overall speed of desiccation than diquat300 was carfentrazone17.5 in 2011. All other treatments exhibited greater overall speed of efficacy than the diquat300 treatments in 2010 compared to 2011. Speed of desiccation with diquat400 was similar to flumioxazin53, flumioxazin71.4 and saflufenacil50 in both site-years. The only treatments that exhibited lower overall efficacy than diquat400 were carfentrazone17.5 and carfentrazone28 in 2011. Stem desiccation with diquat550 exhibited equal or greater speed of efficacy in comparison to other herbicide alone treatments for both site-years.

Leaf desiccation. Speed of desiccation with diquat300 was similar to glufosinate370, carfentrazone28, flumioxazin53 and 71.4, saflufenacil25 and 50 in both site-years. Glufosinate450 in 2010 was the only treatment that exhibited greater speed of efficacy for leaf desiccation than diquat300. Speed of desiccation with diquat400 was greater than carfentrazone17.5 and 28 treatments and similar to all other treatments in both site-years. Diquat550 exhibited greater efficacy of leaf desiccation than glufosinate (370 and 450), flumioxazin53.6 and saflufenacil25 in 2011 and greater efficacy than carfentrazone17.5 and 28 in both site-years. In 2011, no harvest aid treatment desiccated bean leaves greater than diquat treatments.

Pod desiccation. Desiccation with diquat300 was similar to glufosinate370, flumioxazin53 and 71.4, saflufenacil25 and 50 in both site-years. Glufosinate450 in 2010 was the only treatment that exhibited greater efficacy for pod desiccation than diquat300. Desiccation with diquat400 was greater than carfentrazone17.5 and 28 treatments and similar to all other treatments in 2010 (diquat400 desiccated bean pods greater than flumioxazin53.6 in 2011). Diquat550 exhibited greater efficacy of pod desiccation than carfentrazone (17.5 and 28), in both site-years and flumioxazin53.6 in 2011. In 2011, no harvest aid treatment desiccated bean pods greater than the diquat treatments.

3.3.2 Yield and Seed Quality of Bean Seed

Final yield and quality of Pinto bean seed was not affected by any harvest aid herbicides when applied at 80% PCC. In both site-years, yield in Pinto beans was not different among treatments (Table 3.4) and ranged from 1998 kg ha^{-1} to 3082 kg ha^{-1} in 2010 and from 2295 kg ha^{-1} to 2959 kg ha^{-1} in 2011. Seed size and thousand kernel weight also were not significantly different among treatments in both years (Table 3.4).

3.3.3 Moisture Content of Bean Seed

Moisture content of Pinto bean seed was affected by the application of harvest aid herbicides in 2010 but not in 2011 (Table 3.4). Moisture content was significantly greater in treatments containing carfentrazone-ethyl alone and flumioxazin53.6 compared to all other treatments (including the untreated check) in 2010.

Table 3.4 Yield, seed size, thousand kernel weight (TKW) and moisture content (MC) of Pinto bean in 2010 and 2011

	Yield (kg/ha)		Seed Size (cm^2)		TKW (g)		MC (%)	
Treatment g ai ha^{-1}	2010	2011	2010	2011	2010	2011	2010	2011
Untreated	2866	2649	0.76	0.73	333	331	13.8 *D*[a]	11.0
Glyphosate 900	2840	2572	0.75	0.67	331	295	12.8 *D*	10.2
Diquat 300	2525	2364	0.74	0.72	313	305	13.9 *D*	9.6
Diquat 400	2510	2357	0.74	0.68	315	285	14.3 *CD*	10.1
Diquat 550	2048	2547	0.74	0.72	317	309	14.9 *BCD*	9.7
Diquat 300/Glyphosate 900	2451	2597	0.76	0.73	339	318	15.7 *BCD*	10.3
Diquat 400/Glyphosate 900	2281	2295	0.74	0.73	317	320	14.2 *D*	10.2
Diquat 550/Glyphosate 900	2550	2959	0.75	0.70	321	309	12.8 *D*	9.4
Glufosinate 370	2791	2340	0.75	0.71	318	324	12.4 *D*	9.8
Glufosinate 450	2348	2572	0.75	0.71	322	313	13.0 *D*	9.9
Glufosinate 370/Glyphosate 900	2538	2295	0.75	0.72	336	317	12.3 *D*	11.0
Glufosinate 450/Glyphosate 900	2686	2573	0.75	0.70	329	316	12.7 *D*	8.8
Carfentrazone-ethyl 17.5	2436	2501	0.76	0.71	334	304	18.7 *AB*	10.2
Carfentrazone-ethyl 28	1998	2592	0.75	0.71	324	308	22.7 *A*	10.8
Carfentrazone 17.5/Glyphosate 900	2539	2314	0.74	0.70	312	304	12.7 *D*	10.1
Carfentrazone 28/Glyphosate 900	2431	2516	0.75	0.72	321	314	12.8 *D*	9.6
Flumioxazin 53.6	2552	2400	0.75	0.69	329	286	18.5 *ABC*	10.5
Flumioxazin 71.4	2937	2711	0.76	0.72	337	310	12.3 *D*	10.6
Flumioxazin 53.6/Glyphosate 900	2579	2934	0.75	0.71	329	302	13.4 *D*	9.8
Flumioxazin 71.4/Glyphosate 900	3083	2548	0.75	0.71	325	318	12.3 *D*	10.7
Saflufenacil 25	2900	2740	0.74	0.71	315	312	12.6 *D*	10.0
Saflufenacil 50	2751	2303	0.76	0.72	336	308	13.5 *D*	11.2
Saflufenacil 25/Glyphosate 900	3046	2758	0.75	0.72	335	315	12.4 *D*	10.0
Saflufenacil 50/Glyphosate 900	2717	2467	0.75	0.70	326	298	12.7 *D*	10.7

[a]Within columns, means followed by the same letter are not significantly different according to Fisher's protected LSD at the 0.05 level of significance. If there is no letter present, means are not significantly different.

3.3.4 Herbicide Residue Analysis

Herbicides applied in mixture with glyphosate did not affect glyphosate residue levels in seed compared to treatment with glyphosate alone in 2010, while in 2011, several herbicides applied in mixture with glyphosate reduced glyphosate residue levels in bean seed relative to glyphosate900 alone (Figure 3.1). In 2010, the carfentrazone-ethyl mixture treatments exhibited greater glyphosate residue levels compared to all other mixture treatments with the exception of the carfentrazone28/900 treatment and the flumioxazin53.6/900 treatment. In 2011, carfentrazone17.5 exhibited a greater glyphosate residue level than diquat400/900, diquat550/900, glufosinate treatments, carfentrazone28, flumioxazin53.6 and saflufenacil25. Glyphosate900 also exhibited greater glyphosate residue levels than glyphosate mixtures with glufosinate or diquat400 and diquat550. There were no differences among any other treatments.

3.4 Discussion

Over the two years of this study, environmental conditions had a large effect on the relative efficacy of the different harvest aid treatments used. Cool, wet conditions in 2010 made harvest aid application difficult and prolonged the growing season, extending harvest later into the fall. Precipitation during the growing season in 2010 was more than two times the amount that was received in 2011 and was also wetter than normal in comparison to the 30 year average (375 mm) from April to September (Environment Canada 2012). In 2011, warmer temperatures were ideal for harvest aid application and provided optimal conditions for rapid desiccation.

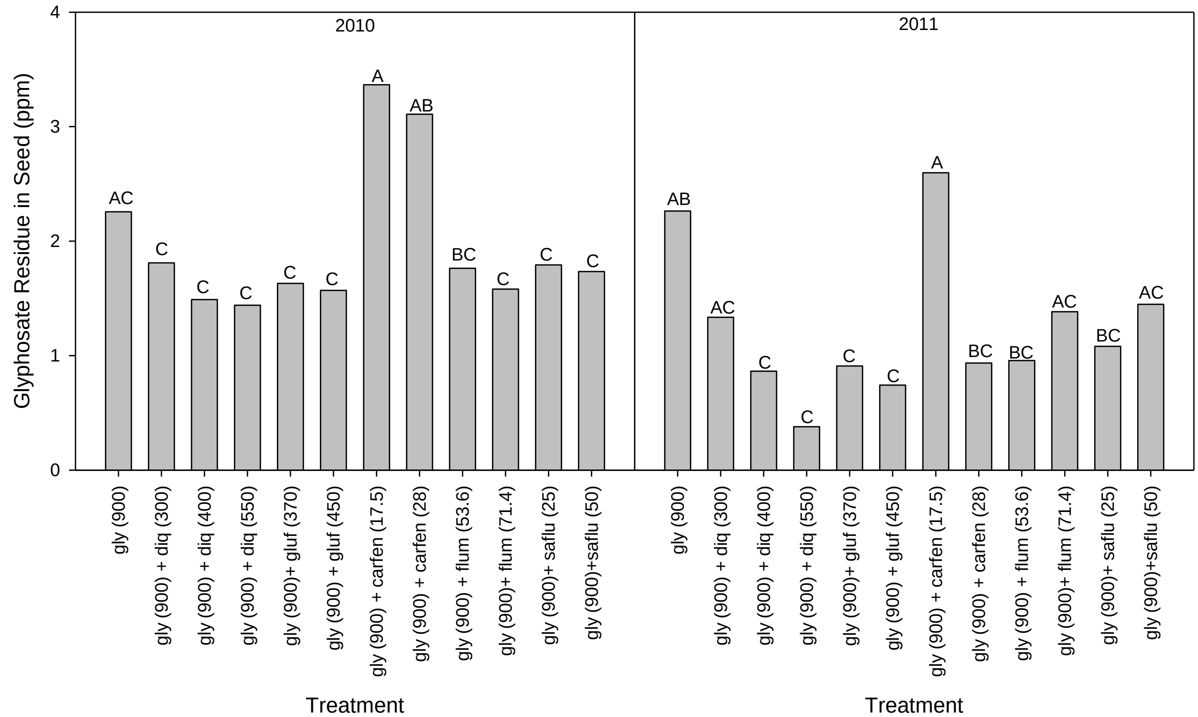

Figure 3.1. The effect of herbicide treatment on glyphosate levels (parts per million) in the Pinto bean seed. Treatments applied were glyphosate (gly), diquat (diq), glufosinate (gluf), flumioxazin (flum) and saflufenacil (saf). For each site-year, means indicated by the same letter are not significantly different according to Fisher’s protected LSD at the 0.05 level of significance.

Statistical analyses were conducted within year due to these obvious differences between site-years. Although not tested statistically, the differing environmental conditions between the two seasons appeared to have affected the speed and efficacy of the harvest aid treatments but did not appear to affect the yield or seed quality in either year. It is possible that the cool, wet environmental conditions at and after the time of application of the harvest aid herbicides in 2010 lead to slower dry down of the bean plants; whereas in 2011, conditions were more optimal for desiccation with the use of harvest aids. This may have been a contributing factor to the observed differences in statistical separation in desiccation among harvest-aid herbicides within site year that were observed between the two years of the study.

The harvest aid herbicides used in this study included systemic and contact herbicides. A systemic herbicide is considered to have the ability to translocate within a plant (either through the xylem or phloem) once they are applied to the plant surfaces (Anonymous 2011a; Baumann et al. 2008; Muzik and Mauldin 1964). Once the herbicide has translocated through the plant it must create a toxic effect to the intended target (depending on mode of action) (Muzik and Mauldin 1964). In comparison, a contact herbicide has limited to no mobility once it has been applied to plant foliage (Anonymous 2011a; Baumann et al. 2008, Ross and Childs 1996; Ware and Whitacre 2004).

Glyphosate is a group 9 systemic herbicide that affects amino acid synthesis in plants and is transported through the plant tissues through phloem and xylem movement

(Anonymous 2011a; Ross and Childs 1996; Ware and Whitacre 2004). Due to the systemic activity of glyphosate, symptoms can take 5-7 days to develop and death often will not occur for up to 14 days (Anonymous 2012b; Baumann 2008; Senseman 2007). Glufosinate (group 10) and diquat (group 22) are fast acting contact herbicides that begin to desiccate plants within 3-5 days after application (Anonymous 2011b; Baumann 2008; Ross and Childs 1996; Senseman 2007). Carfentrazone-ethyl, flumioxazin and saflufenacil are group 14 PPO inhibitors; however, carfentrazone-ethyl is strictly a contact herbicide while flumioxazin and saflufenacil are contact herbicides with limited systemic activity (Anonymous 2012a; Dayan 1997, Grossman 2011; Senseman 2007). Initially, it was presumed that type of herbicide would have an effect on overall speed and efficacy of desiccation however, in this study; type of herbicide (systemic or contact herbicide) did not appear to affect speed of desiccation, final desiccation or seed residue levels.

Glufosinate exhibited the most consistent efficacy at desiccating bean plant organs over the two years with distinctly different environments during seed maturation. That no difference in efficacy was observed on all plant parts desiccated with glufosinate (applied alone or in mixture with glyphosate) was unexpected due to the nature of activity of glufosinate and the environmental conditions under which applications were made. Efficacy of glufosinate is highly sensitive to adverse environmental conditions (cool temperatures, low to moderate humidity) at the time of application and is improved by hot, humid conditions at application (Anonymous 1998; Peterson and Hurle 2001; Senseman 2007; Steckel et al. 1997). Although adverse conditions in 2010 were not ideal for glufosinate it seems that these conditions did not influence its performance as a desiccant. Since most research on glufosinate use is as an in-crop herbicide application as opposed to its use as a desiccant (as in this study), our results suggest that the efficacy of glufosinate may not be as sensitive to environmental conditions when used as a desiccant. A contribution of natural senescence cannot be excluded from this observation, however. perhaps it is not as sensitive to environmental conditions when used in non-herbicidal use patterns.

Carfentrazone-ethyl was the least effective of the active ingredients investigated in this study. The efficacy of the carfentrazone-ethyl treatments was inconsistent, and in 2010, no treatment containing carfentrazone-ethyl provided complete desiccation for any of the investigated plant organs. Carfentrazone-ethyl is limited by poor mobility within the plant and therefore adequate spray coverage is required in order to ensure complete desiccation of the plant (Griffin et al. 2010; Senseman 2007). Studies conducted by Sprague (2009, 2012) reaffirm these results about the reduction in overall quality when using carfentrazone-ethyl as a harvest aid herbicide in dry bean production. The overall trend among all plant parts desiccated with carfentrazone-ethyl was that the addition of glyphosate increased the speed and efficacy of desiccation when compared to carfentrazone-ethyl alone.

Based on the literature, carfentrazone-ethyl was expected to be one of the faster acting contact herbicides used in this study. Injury symptoms can be visible within hours of application and plant death occurs within days of application (Griffin et al 2010;

Senseman 2007). In contrast to the literature, carfentrazone-ethyl, even at the high dose, showed reduced speed of desiccation in this study and this likely facilitated increased translocation of glyphosate to the seeds of Pinto beans. Dayan et al. (1997) showed differential activity of carfentrazone-ethyl among plant species. It is possible that bean species may be more tolerant to this herbicide as soybean (*Glycine max* [L.] Merr.), also a legume crop, exhibited reduced efficacy and increased metabolism of carfentrazone-ethyl compared to Ivyleaf morning glory (*Ipomoea hereacea*) and velvetleaf (*Abutilon theophrasti*) (Dayan et al 1997).

Glyphosate residue levels in the seed are an important consideration, especially when the harvested product is bound for export markets. There are set international standards to regulate the concentration of pesticide residues, known as maximum residue limits (MRL) (Table 2.1). For glyphosate residues in dry bean seed, different nations have differing sensitivities to the allowable MRL in the harvested product. The European Union and Japan (major export markets for Canadian dry beans) have MRLs of 2 parts per million (ppm) for glyphosate while the MRL for Canada is 4 ppm (Food and Agricultural Organization 2010, Foreign Agricultural Service 2012). Only five treatments in this study exceeded the MRL for the European Union and Japanese markets. Application of glyphosate alone and carfentrazone-ethyl17.5 exceeded the MRL of 2 ppm at both site-years and carfentrazone-ethyl28 also exceeded the MRL in 2010. Glyphosate residue in the seed ranged from 1.5 ppm to a maximum 3.4 ppm in 2010 and from 0.4 ppm to 2.6 ppm in 2011. In this study, statistical analysis was not able to clearly separate treatments based on MRL values and statistically similar treatments included values above and below the MRL of 2 ppm. Despite a lack of statistical separation among these treatments, the biological reality of the MRL cut-off must be taken into consideration as treatments above this level would clearly be rejected by affected export markets. Although there were only five treatments that exceeded the MRL for glyphosate in this study, many treatments were close to the 2 ppm limit.

Yield, seed size and thousand kernel weight were not affected adversely (statistically or biologically) by the different harvest aid herbicides applied in this study. This suggests that the application of harvest aid herbicides should not affect overall quality when applied at the recommended dose and appropriate stage of development of the bean plants. Studies conducted previously by Ratanayke and Shaw (1992) and Wilson and Smith (2002) exhibited similar results in soybean and dry bean. In 2010, the moisture content of Pinto bean seed was significantly greater in three treatments (both carfentrazone-ethyl treatments and flumioxazin53.6) than all other treatments. There is no clear explanation for this. These treatments had amongst the slowest desiccation speeds, however, speed of desiccation and final desiccation ratings were not significantly different from other treatments that did not show elevated seed moisture content at harvest.

Based on the results from this experiment carfentrazone-ethyl is likely not a viable option for Manitoba producers due to its apparent ineffectiveness as a desiccant, in mixture with glyphosate or applied alone. Saflufenacil, flumioxazin, glufosinate and diquat all seem to be reasonable desiccant options to be applied in mixture with glyphosate in terms of consistency, efficacy and the ability of the mixture to reduce the potential accumulation of glyphosate in the seed. Ashigh and Hall (2010) speculated that the contact activity of saflufenacil causes rapid cell death which limits the ability of the glyphosate to translocate throughout the plant and studies by Jordan et al. (1997) corroborate these findings. From the results of this study, it appears that diquat, flumioxazin and glufosinate have a similar effect on glyphosate translocation as saflufenacil.

3.5 Conclusion

This research has demonstrated that the addition of a contact herbicide to glyphosate does not affect seed yield or quality of dry beans when applied as a harvest aid at physiological maturity. The mixture of diquat, glufosinate, flumioxazin and saflufenacil with glyphosate reduced the level of glyphosate that translocated through the plant and into the seed. These contact herbicides were more effective than others at drying down the plant tissue and this seemed to be related to the reduced level of glyphosate movement. Aside from physical properties of the herbicides, environmental conditions also had a marked effect on the overall efficacy of the contact herbicides.

4.0 EFFECT OF APPLICATION TIMING OF TWO HARVEST AID HERBICIDES (GLYPHOSATE AND SAFLUFENACIL) ON ACCUMULATION OF RESIDUE IN DRY BEAN SEED

Abstract. Field experiments were conducted in 2010 and 2011 to determine the effect of saflufenacil alone and in mixture with glyphosate on dry bean desiccation, yield, seed quality and residue accumulation of glyphosate and its metabolite aminomethylphosphonic acid (AMPA) in the seed at 5 different stages of development of pinto bean. Windbreaker pinto beans were treated with saflufenacil, glyphosate or a saflufenacil/glyphosate tank-mix at the 0, 25, 50, 75 and 100% PCC stages of development. Glyphosate applied alone at 0 and 25% PCC desiccated all plant parts significantly slower than any treatment containing saflufenacil. The application of harvest aid herbicides prior to 75% PCC had an effect on final seed yield and overall seed quality. In 2010, the addition of saflufenacil did not affect the level of residue of glyphosate or AMPA in the pinto bean seed. The level of residues decreased in all treatments when the harvest aid herbicides were applied at later stages of crop development. In 2011, the addition of saflufenacil to glyphosate decreased the level of residues in the seed when applied at the earlier stages of development. These results indicate that the addition of an effective contact herbicide may improve the overall efficacy of glyphosate alone and reduce potential residues in the seed when applied at the appropriate stage of crop development.

4.1 Introduction

Dry beans often exhibit an indeterminate growth habit and frequently this growth habit and spatial variability often result in uneven maturation within a field. To alleviate uneven maturation, growers generally use a broad spectrum herbicide to assist harvest by desiccating the bean plants and providing late season weed control (Anonymous 2006). Herbicides currently registered and used by producers for application to dry bean prior to harvest are glyphosate (commercial name Roundup), carfentrazone-ethyl (Aim), glufosinate ammonium (Ignite) and diquat (Reglone) (Anonymous 2013).

Saflufenacil is a new broad spectrum group 14 herbicide that is registered for use in pre- and post-seed applications, chemical fallow and desiccant applications (Anonymous 2013; Grossman et al. 2011; Knezevic et al. 2009; Soltani et al. 2009). Saflufenacil has many characteristics of an ideal desiccant including providing rapid dry down of plant tissue, low use rates, contact and systemic activity and is deemed to have a low environmental, toxicological and ecotoxicological impact (Knezevic et al. 2009; Soltani et al. 2009). Studies by Knezevic et al. (2009) have found that the addition of saflufenacil to glyphosate can provide a synergistic effect and improve the efficacy of both herbicides. This is in contrast to a study by Ashigh and Hall (2010) that suggests that a saflufenacil and glyphosate tank-mix may actually hinder the ability of glyphosate to translocate through the plant due to the rapid activity of saflufenacil. For this study, saflufenacil was chosen as the tank mix partner with glyphosate due to the potential that saflufenacil has shown as a desiccant in other studies.

The recommended application time of harvest aid herbicides is when 80% of the bean pods have begun to change colour. This colour change signifies that the bean plant has reached physiological maturity (Wilson and Smith 2002). Application timing of a harvest aid herbicide is critical as it may affect final yield or result in unacceptable residues in the seed (Cessna et al. 2000; Cessna et al. 2002). The amount of residue that accumulates in crop seed by harvest aid herbicides appears to depend primarily on the stage of development of the crop at the time of harvest herbicide application (Azlin and McWhorter 1981; Cessna et al. 2000; Cessna et al. 2002). Studies by Baig et al. (2003) and Cessna et al. (2000 and 2003) demonstrate that as a crop approaches physiological maturity, the amount of glyphosate that is translocated through the plant and accumulates within the seed typically decreases compared to the same treatment applied at earlier stages of development.

The objective of this study was to evaluate the use of saflufenacil alone and in mixture with glyphosate applied at different stages of maturation as possible harvest aids for use in Manitoba dry bean production and to determine if these herbicides are capable of providing fast, uniform dry down of bean plants; while eliminating chemical residues from the seed as per international maximum residue level standards.

4.2 Methods and Materials

4.2.1 Site Establishment

Field experiments were established in Carman, Manitoba as outlined in Chapter 3: Evaluation of Tankmixing Contact Herbicides with Glyphosate at Pre-harvest Timing on the Accumulation of Residues in Dry Bean Seed (page 27). In brief, site was treated equally for this experiment as was the previously explained experiment in Chapter 3.

4.2.2 Experimental Design

This experiment was a 2-way factorial with control structured in a randomized complete block design (RCBD) with four replicates. The replicates served as blocks. The factors involved were time of application of the harvest aid herbicides and the herbicide treatment applied. Harvest aid herbicides consisted of glyphosate alone, saflufenacil alone or a glyphosate/saflufenacil mixture and were applied at five different times of application. The times of application were 0%, 25%, 50%, 75% and 100% PCC. Each block contained a total of 16 treatments consisting of 15 different herbicide treatments and an untreated control.

4.2.3 Dry Bean Establishment

Planting for this experiment occurred concurrently to the experiment described in Chapter 3. Cultivar, seed treatment, seeding rate and planting depth were as described in Chapter 3.

4.2.4 In-Crop Weed Control

In 2010 and 2011, plots were treated equally to the experiment outlined in Chapter 3. In brief, all in-crop weed control was executed the same across both experiments (manually and chemically).

4.2.5 Harvest Aid Application

Three harvest aid herbicide treatments were applied at 5 different stages of seed development. Herbicide treatments consisted of glyphosate alone (900 g ai ha^{-1}), saflufenacil alone (50 g ai ha^{-1}, Merge adjuvant 0.5% v/v) and a glyphosate/saflufenacil mixture (900 g ai ha^{-1}/50 g ai ha^{-1}; Merge adjuvant 0.5% v/v). Treatments were applied when the bean crop was at developmental stages of 0% PCC, 25% PCC, 50% PCC, 75% PCC and 100% PCC. In 2010, no harvest aid herbicides were applied at the 25% PCC time of application due to an application error where the appropriate stage of maturation was missed and it was decided to eliminate the maturation stage instead of making the late application. Harvest aid herbicide application dates and environmental conditions at time of application are summarized in Table 4.1. All harvest aid herbicides were applied as described in the previous chapter.

4.2.6 Measurements

Desiccation ratings, dry bean yield, seed size, thousand kernel weight and residue analysis measurements were taken, evaluated and calculated in the same manner as described in Chapter 3.

4.2.7 Statistical Analysis

The speed of desiccation of Pinto bean plants was calculated using the area under the desiccation progress curve (AUDPC) as described in Chapter 3. The fixed effects in the model included herbicide treatment and time of application and replicate was considered random. The model used to test these effects was an augmented factorial experimental design structure (Marini 2003) as this experiment was a 3 x 5 factorial plus an untreated control. The three herbicide treatments (glyphosate alone, saflufenacil alone and glyphosate/saflufenacil mixture) were applied at five different stages of maturity (0%, 25%, 50%, 75% and 100% PCC). The interaction between the herbicide treatment and the time of application was also tested. Normality of residuals and outliers were determined as described in Chapter 3.

When the residuals of a response variable did not conform to the normal distribution, the data were subjected to a $\log_{10}$ transformation prior to analysis. Transformed means were back transformed to original scale for the presentation of results. For significant model effects, the means were separated based on Fisher's protected LSD (<0.05) using the pdmix800 macro (Saxton 1998).

Table 4.1 Harvest aid herbicide application date, time of application treatment (pod colour change (PCC)) and environmental conditions (temperature, relative humidity, and wind speed at an elevation of 268.2 m) at each time of application for the 2010 and 2011 experiments.

Site-year	Application Date	Time of Application (PCC)	Temperature (°C)	Relative Humidity	Wind (km/hr)
2010	September 3	0%	15	72%	NNW 21
2010	September 8	50%	13	67%	SE 9
2010	September 11	75%	15	55%	W 25
2010	September 24	100%	13	71%	NNW 13
2011	August 23	0%	19	78%	W 13
2011	August 25	25%	20	55%	SW 13
2011	August 29	50%	21	64%	N 11
2011	September 2	75%	17	66%	W 15
2011	September 14	100%	8	63%	N 15

4.3 Results

4.3.1 Efficacy and Speed of Desiccation

As described in Chapter 3, AUDPCs were used to determine speed and efficacy of the harvest aid treatments. In treatments with equal final desiccation ratings of the target organs (Table 4.2), differences in the AUDPC among the treatments are indicative of the speed of desiccation.

4.3.1.1 Stem Desiccation

The speed of stem desiccation in Pinto bean plants was affected by the main effects only (no interaction between the time of application of harvest aid treatment and herbicide applied) in 2010 (Figure 4.1) and by an interaction between the main effects in 2011 (Figure 4.2). In 2010, saflufenacil alone or in mixture resulted in faster desiccation of bean stems than glyphosate alone. As the time of application approached 100% PCC, AUPDC increased, indicating a quicker dry down of the stem tissue. In 2011, an interaction occurred between glyphosate alone and the glyphosate+saflufenacil mixture treatments and another interaction was observed between the saflufenacil alone and the glyphosate+saflufenacil mixture treatments. The speed of desiccation of the stem of Pinto bean plants was slower when treated with the glyphosate alone compared to when treated with the glyphosate+saflufenacil mixture at 0%, 25%, 50% and 75% PCC (no difference among treatments at 100% PCC). At the 0% and 25% PCC times of application, the speed of desiccation of the stem of Pinto beans was also slower when treated with the saflufenacil alone compared to the glyphosate+saflufenacil mixture.

Table 4.2. Desiccation (% Des.) of stems, leaves and pods at 16 days after application (DAA) of Pinto bean in 2010 and 2011

		Stem % Des.		Leaf % Des.		Pod % Des.	
Treatment	Time of Application (%PCC)[z]	2010	2011	2010	2011	2010	2011
Glyphosate	0%	94*	90*	99	95*	98*	92*
Glyphosate	25%	nd[a]	94*	nd[a]	98*	nd[a]	95*
Glyphosate	50%	92*	95*	99	98*	92*	97*
Glyphosate	75%	99	95*	99	99	99	98*
Glyphosate	100%	99	99	99	99	99	99
Saflufenacil	0%	86*	90*	99	97*	95*	86*
Saflufenacil	25%	nd[a]	96*	nd[a]	99	nd[a]	96*
Saflufenacil	50%	87*	98*	93*	99	90*	99
Saflufenacil	75%	99	99	99	99	99	99
Saflufenacil	100%	99	99	99	99	99	99
Glyphosate/Saflufenacil	0%	93*	99	99	99	99	99
Glyphosate/Saflufenacil	25%	nd[a]	99	nd[a]	99	nd[a]	99
Glyphosate/Saflufenacil	50%	93*	99	99*	99	96*	99
Glyphosate/Saflufenacil	75%	99	99	99	99	99	99
Glyphosate/Saflufenacil	100%	99	99	99	99	99	99
$LSD_{0.05}$		n.s	n.s	n.s	n.s	n.s	n.s

[a]no data (nd) recorded for 25% PCC treatments in 2010

[z]% Pod Colour Change (PCC)

*indicates treatments with final mean ratings of 99% desiccation were not included in statistical analysis due to a lack of variation among the replicates

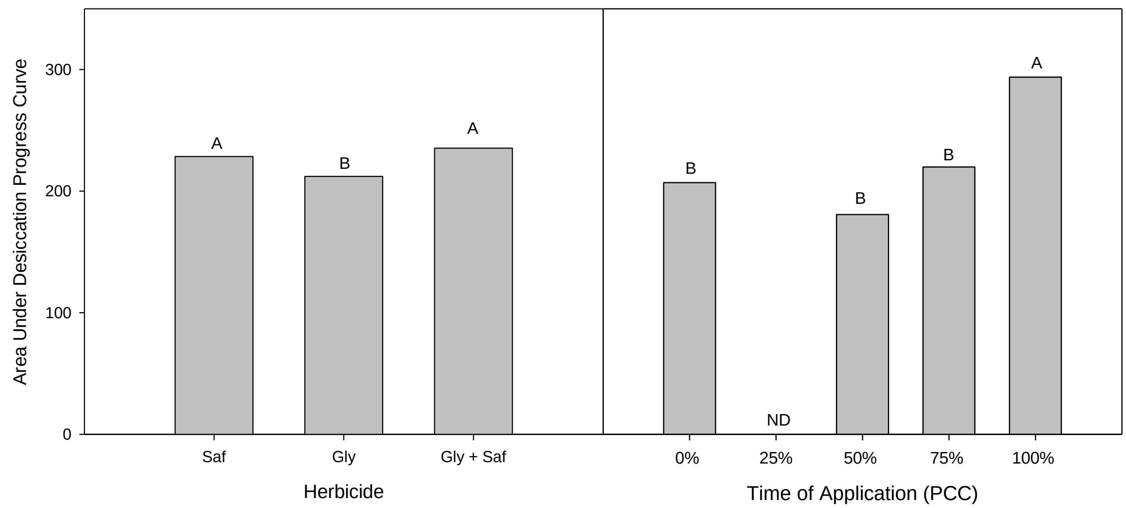

Figure 4.1. The effect of harvest aid herbicide treatment and the time of application on area under the desiccation progress curve for stem desiccation in 2010. Treatments of saflufenacil alone (Saf), glyphosate alone (Gly) and a glyphosate+saflufenacil mixture (Gly+Saf) were applied at 0%, 25%, 50%, 75% and 100% PCC. No data (ND) was collected at the 25% time of application (refer to Chapter 4.2 Methods and Materials - Section 4.2.5). Within each panel, means associated with the same letter are not significantly different according to Fisher’s protected LSD at the 0.05 level of significance.

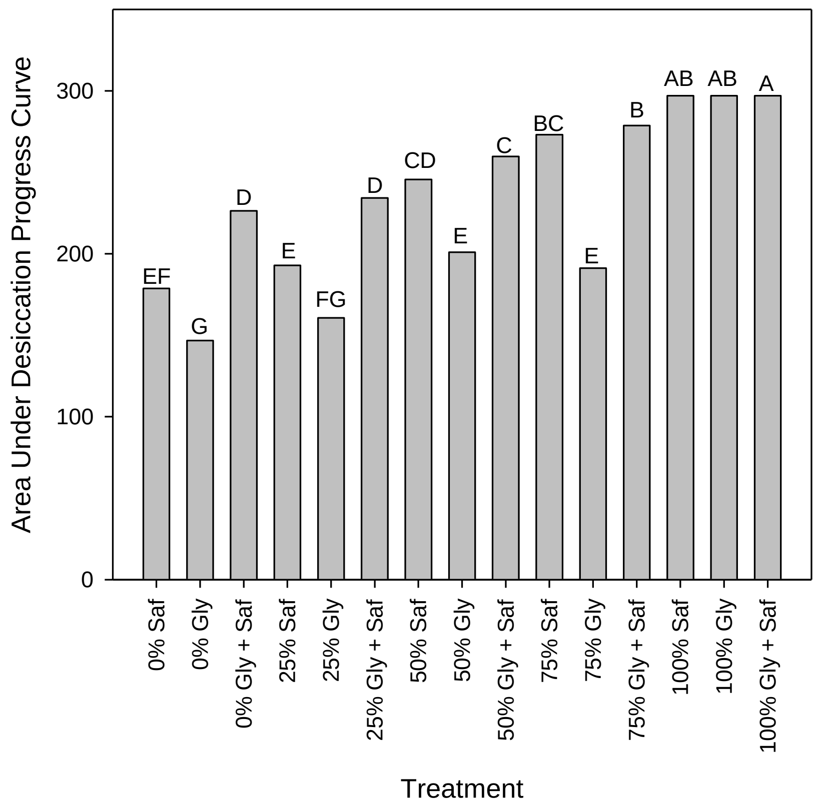

Figure 4.2. The interaction between herbicide treatment and time of herbicide application on the speed of desiccation on Pinto bean stems in 2011. Treatments of saflufenacil alone (Saf), glyphosate alone (Gly) and a glyphosate+saflufenacil mixture (Gly+Saf) were applied at 0%, 25%, 50%, 75% and 100% PCC. Means associated with the same letter are not significantly different according to Fisher's protected LSD at the 0.05 level of significance.

There was no difference in desiccation between these two treatments at 50%, 75% and 100% PCC. The speed of desiccation was slower in all glyphosate alone treatments compared to the saflufenacil alone treatments at all times of application, except at 100% PCC.

4.3.1.2 Pod and Leaf Desiccation

Interactions between the two main effects (time of application and herbicide treatment) were observed (Figure 4.3 and Figure 4.4) in both years for pod and leaf desiccation. One interaction occurred between the glyphosate alone and the glyphosate+saflufenacil mixture treatments and another interaction was observed between the saflufenacil alone and the glyphosate+saflufenacil mixture treatments. In both years, the speed of desiccation of Pinto bean pods and leaves was slower when treated with glyphosate alone compared to the glyphosate+saflufenacil mixture treatments at 0%, 25%, 50% and 75% PCC, but not when applied at 100% PCC. In 2010, the saflufenacil alone and the glyphosate+saflufenacil mixture treatments were only different at the 50% PCC time of application. At the 50% PCC time of application, the saflufenacil alone treatment exhibited a slower speed of desiccation than the glyphosate+saflufenacil mixture, but, was similar to the speed of desiccation to the glyphosate alone treatment. The 50% and 100% PCC time of application were the only instances where the glyphosate alone and the saflufenacil alone treatments were similar, at all other times of application the saflufenacil alone treatment desiccated Pinto bean pods and leaves more rapidly than the glyphosate alone treatment. In 2011, the speed of desiccation of Pinto bean pods and

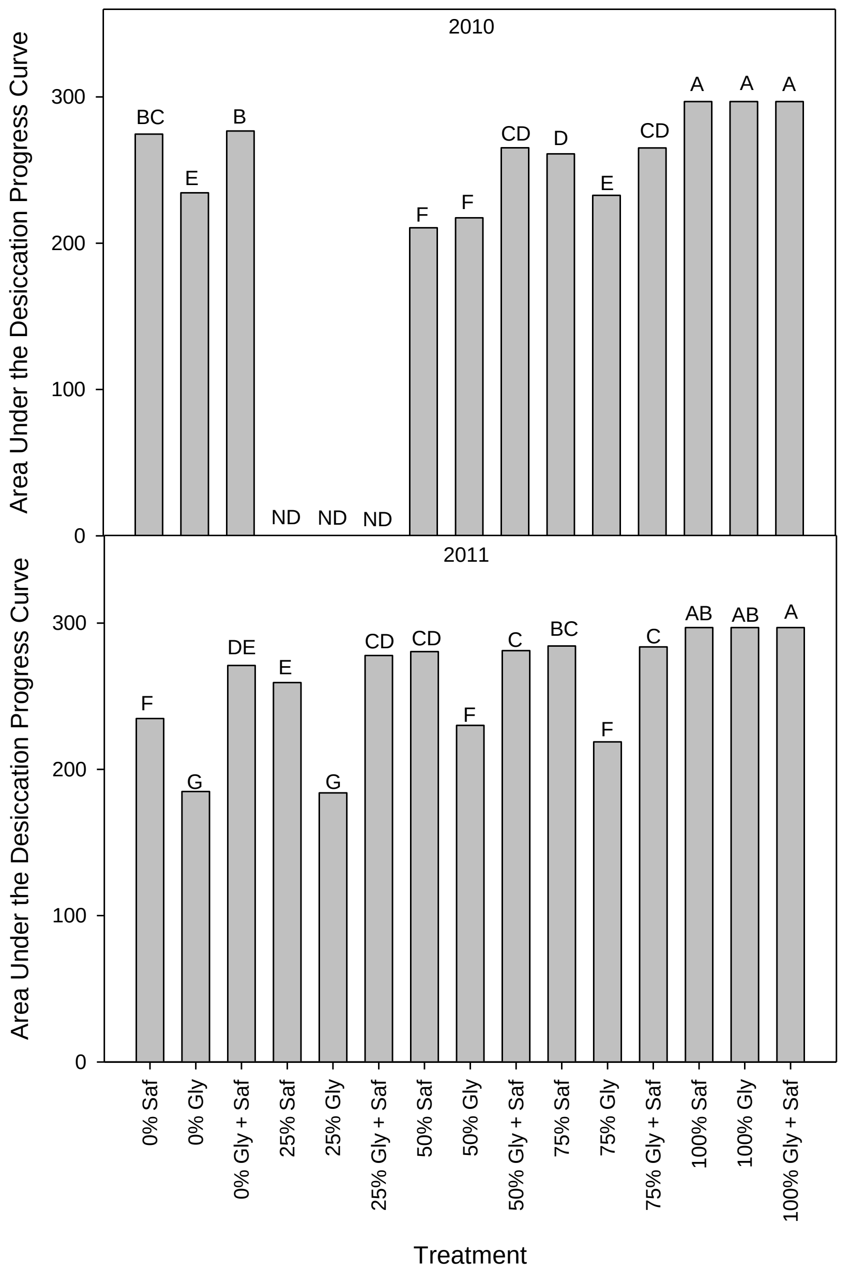

Figure 4.3. The interaction between herbicide treatment and time of herbicide application on the speed of desiccation on Pinto bean leaves. Treatments of saflufenacil alone (Saf), glyphosate alone (Gly) and a glyphosate+saflufenacil mixture (Gly+Saf) were applied at 0%, 25%, 50%, 75% and 100% pod colour change. No data (ND) was collected at the 25% time of application. (refer to Chapter 4.2 Methods and Materials - Section 4.2.5) Within each site-year, means associated with the same letter are not significantly different according to Fisher's protected LSD at the 0.05.

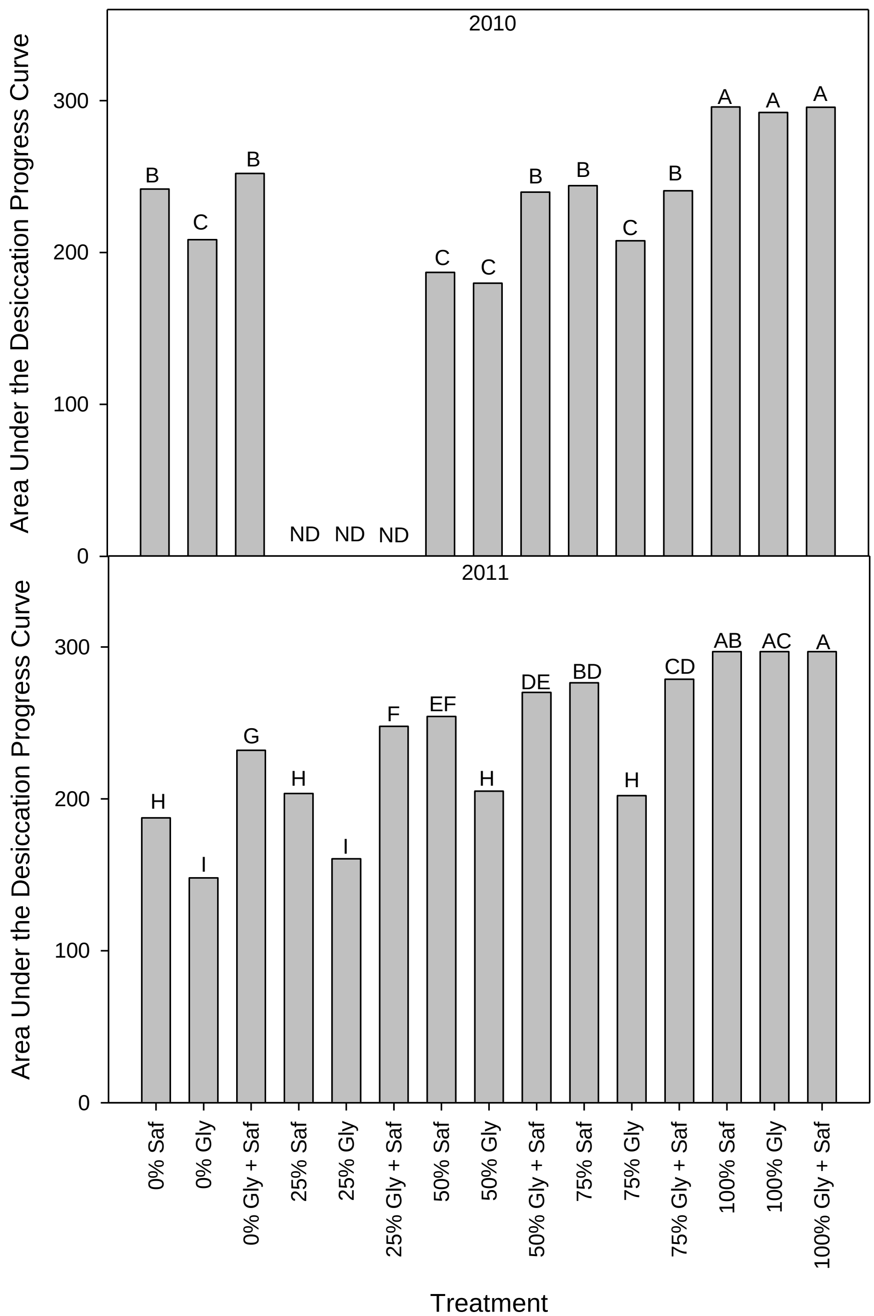

Figure 4.4. The interaction between herbicide treatment and time of herbicide application on the speed of desiccation on Pinto bean pods. Treatments of saflufenacil alone (Saf), glyphosate alone (Gly) and a glyphosate+saflufenacil mixture (Gly+Saf) were applied at 0%, 25%, 50%, 75% and 100% pod colour change. No data (ND) was collected at the 25% time of application (refer to Chapter 4.2 Methods and Materials - Section 4.2.5). Within each site-year, means associated with the same letter are not significantly different according to Fisher’s protected LSD at the 0.05.

leaves was slower when treated with saflufenacil alone when compared to the glyphosate+saflufenacil mixture treatment at the 0% and 25% PCC times of application. There was no difference in the speed of desiccation between these two treatments at 50%, 75% and 100% PCC. The speed of desiccation of all glyphosate alone treatments was slower compared to the saflufenacil alone treatments at 0%, 25%, 50% and 75% PCC (no difference among treatments at 100% PCC).

4.3.2 Yield

In both crop years, final Pinto bean yield was significantly affected by the application of the different harvest aid herbicide treatments. Yield was affected only by time of application of the desiccation treatments (Figure 4.5) in 2010. At the 0% PCC time of application, crop yield was significantly lower than at the 75% and 100% PCC times of application and the untreated control; however, was not different from the 50% PCC time of application. The maximum difference in bean yield between all treatments was about 30% (untreated control vs. 0% PCC).

Bean yield was affected by interactions between the two main effects (time of application and herbicide treatment) (Figure 4.5) in 2011. One interaction occurred between the glyphosate alone and the glyphosate+saflufenacil mixture treatments and another interaction was observed between the saflufenacil alone and the glyphosate+saflufenacil mixture treatments. At the 0% and 25% PCC times of application, yield of Pinto beans treated with the glyphosate+saflufenacil mixture was lower than when treated with glyphosate alone whereas at the 50% PCC time of application the yield of Pinto beans

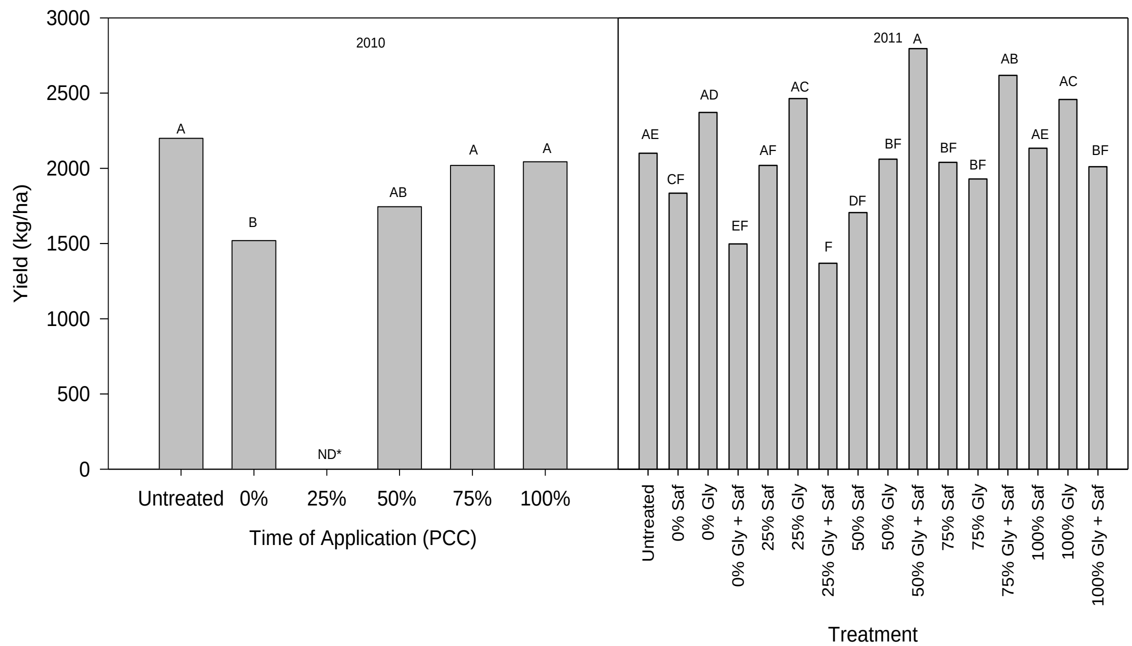

Figure 4.5. The effect of time of herbicide application (2010) and the interaction between herbicide treatment and time of herbicide application (2011) on final yield. Treatments applied were saflufenacil alone (Saf), glyphosate alone (Gly) and a glyphosate+saflufenacil mixture (Gly+Saf) at 0%, 25%, 50%, 75% and 100% pod colour change (PCC). No data was collected at the 25% time of application (ND) (refer to Chapter 4.2 Methods and Materials - Section 4.2.5). Within each site-year, means indicated by the same letter are not significantly different according to Fisher's protected LSD at the 0.05 level of significance.

treated with the glyphosate+saflufenacil mixture was greater than when treated with glyphosate alone. No differences were observed among the glyphosate alone and the glyphosate+saflufenacil treatments at the remaining times of application.

Results for saflufenacil alone compared to the glyphosate+saflufenacil mixture treatment were inconsistent in that there were no differences in yield between these treatments at 0%, 25%, 75%, and 100% PCC. At 50% PCC, however, yield of Pinto beans was greater when treated with the glyphosate+saflufenacil mixture compared to saflufenacil alone. The glyphosate+saflufenacil mixture treatment demonstrated both the highest bean yields (50% and 75% PCC time of application) and the lowest bean yields (0% and 25% PCC time of application) of all treatments indicating that the time of application of this treatment combination may be critical with respect to bean yield. Pinto bean yield was unaffected by time of application when treated with glyphosate or saflufenacil alone. The difference between the highest yielding (50% glyphosate+saflufenacil mixture) and the lowest yielding treatment (25% glyphosate+saflufenacil mixture) was about two-fold.

4.3.3 Seed Size

In both site-years, the different harvest aid herbicides applied at the various PCCs affected the overall seed size of Pinto beans. Seed size was affected only by time of application of the harvest aid herbicide treatment (Figure 4.6) in 2010. Seed size was significantly larger at the 100% PCC than all other times of application, however, all time of application treatments were similar to the untreated control. Overall, there was a

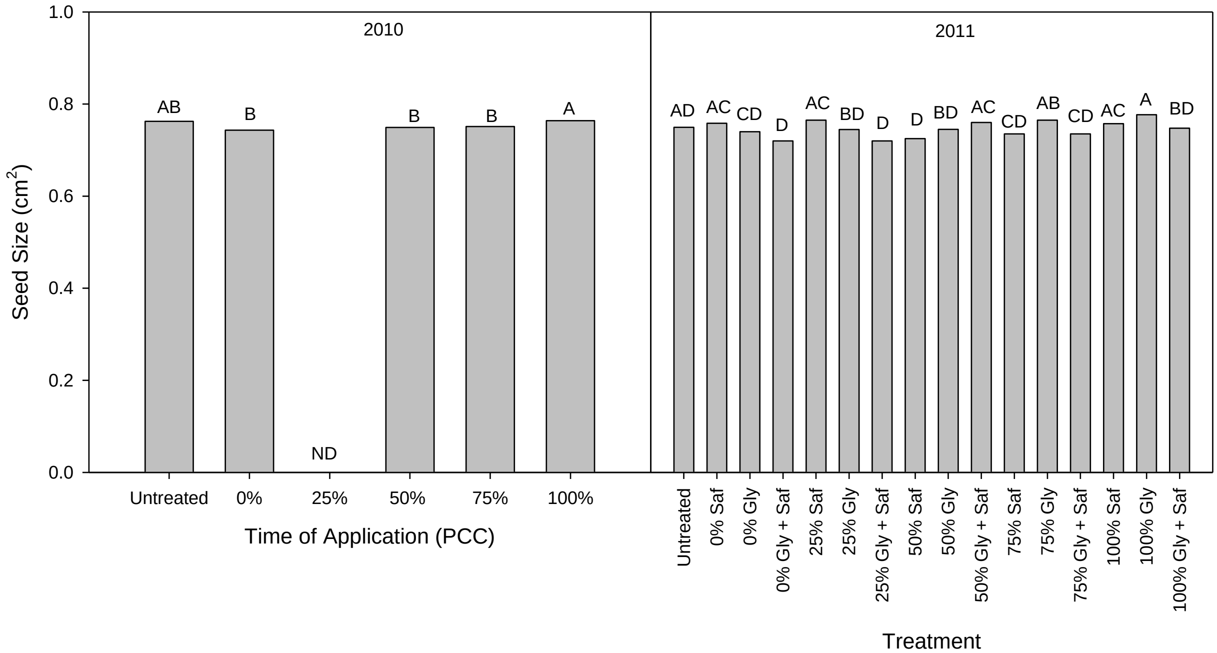

Figure 4.6. The effect of time of herbicide application (2010) and the interaction between herbicide treatment and time of herbicide application (2011) on seed size. Treatments applied were saflufenacil alone (Saf), glyphosate alone (Gly) and a glyphosate+saflufenacil mixture (Gly+Saf) at 0%, 25%, 50%, 75% and 100% pod colour change (PCC). No data was collected at the 25% time of application (ND) (refer to Chapter 4.2 Methods and Materials - Section 4.2.5). Within each site-year, means indicated by the same letter are not significantly different according to Fisher's protected LSD at the 0.05 level of significance.

maximum difference of about 3% in seed size of Pinto bean between the largest (100% PCC) and the smallest (0% PCC) seeds.

Interactions between the main effects (harvest aid herbicide treatment and time of application) in 2011 (Figure 4.6) were observed and affected seed size. An interaction occurred between the glyphosate alone and the glyphosate+saflufenacil mixture treatments and another interaction was observed between the saflufenacil alone and the glyphosate+saflufenacil mixture treatments. At the 75% and 100% PCC times of application, seed size of Pinto beans treated with the glyphosate+saflufenacil mixture was lower than when treated with glyphosate alone, while no differences were observed between these treatments at any other time of application. Results for the saflufenacil alone treatments compared to the glyphosate+saflufenacil mixture treatments were inconsistent in that there were no differences in seed size between these treatments at the 75% and 100% PCC time of application; however, seed size was larger at the 50% PCC time of application and smaller at the 0% and 25% PCC times of application for Pinto beans treated with the glyphosate+saflufenacil mixture compared to saflufenacil alone. At the 75% PCC time of application seed size of Pinto beans treated with glyphosate alone was larger than when treated with saflufenacil alone. There were no differences in Pinto bean seed size between these two treatments at any other time of application. A maximum difference of about 7% in seed size of Pinto bean was observed among treatments with the largest (100% glyphosate alone) and the smallest (0% and 25% glyphosate+saflufenacil, 50% saflufenacil alone) seeds.

4.3.4 Thousand Kernel Weight

In both site-years, the different harvest aid herbicides applied at the various timings affected the overall thousand kernel weight of Pinto bean seeds. In 2010, thousand kernel weight (TKW) of Pinto bean was influenced only by time of application of the desiccant treatments (Figure 4.7). Pinto bean TKW was lower at the 0% PCC time of application than the untreated control, the 75% and the 100% PCC treatments. There was no difference in Pinto bean TKW between the 0% and 50% PCC times of application or between the 50% and 75% PCC times of application. Overall, there was a maximum difference of about 6% in TKW of Pinto bean among treatments with the greatest (100% PCC time of application) and the lowest (0% PCC time of application) TKWs in 2010.

In 2011, thousand kernel weight of Pinto bean was affected by an interaction between harvest aid herbicide treatment and time of application (Figure 4.7). One interaction occurred between the glyphosate alone and the glyphosate+saflufenacil mixture treatments and another interaction was observed between the saflufenacil alone and the glyphosate+saflufenacil mixture treatments. At the 0%, 25%, and 100% PCC times of applications, TKW of Pinto beans treated with the glyphosate+saflufenacil mixture was lower than when treated with the glyphosate alone, while no difference was observed between these treatments at the remaining times of application. Results for the saflufenacil alone treatment compared to the glyphosate+saflufenacil mixture treatment were inconsistent. At the 0%, 75% and 100% PCC times of application there were no differences in Pinto bean TKW among the treatments, however, TKW was greater at the

50% PCC time of application and lower at the 25% PCC time of application for Pinto beans treated with the glyphosate+saflufenacil mixture compared to the saflufenacil alone treatments. TKW of Pinto bean was unaffected by time of application when treated with glyphosate or saflufenacil alone. There was a maximum difference of about 15% in TKW of Pinto bean among the treatments with the greatest (100% glyphosate alone and 100% saflufenacil alone) TKW and the lowest (0% and 25% glyphosate+saflufenacil mixture) TKW.

4.3.5 Seed Moisture Content

In both site-years, the different harvest aid herbicides applied at the various time of applications affected the MC of Pinto bean seeds. Seed moisture content in 2010 was affected only by herbicide application (Figure 4.8). The Pinto bean seed MC in the untreated control and the saflufenacil alone treatments were significantly greater than the Pinto bean seed MC in the glyphosate alone and the glyphosate+saflufenacil mixture treatments. Pinto bean seed MC was affected only by time of application of the harvest aid treatments (Figure 4.8) in 2011. At the 0% PCC time of application, Pinto bean seed MC was significantly lower than the untreated control, the 50% and the 100% PCC treatments. At the 75% PCC time of application, Pinto bean seed MC was significantly lower than the 100% PCC time of application. There were no differences in Pinto bean MC among other treatments. Overall, there was a difference of about 14% in Pinto bean seed MC among the treatments with the greatest (100% PCC time of application) MCs and the lowest (0% PCC time of application) MCs.

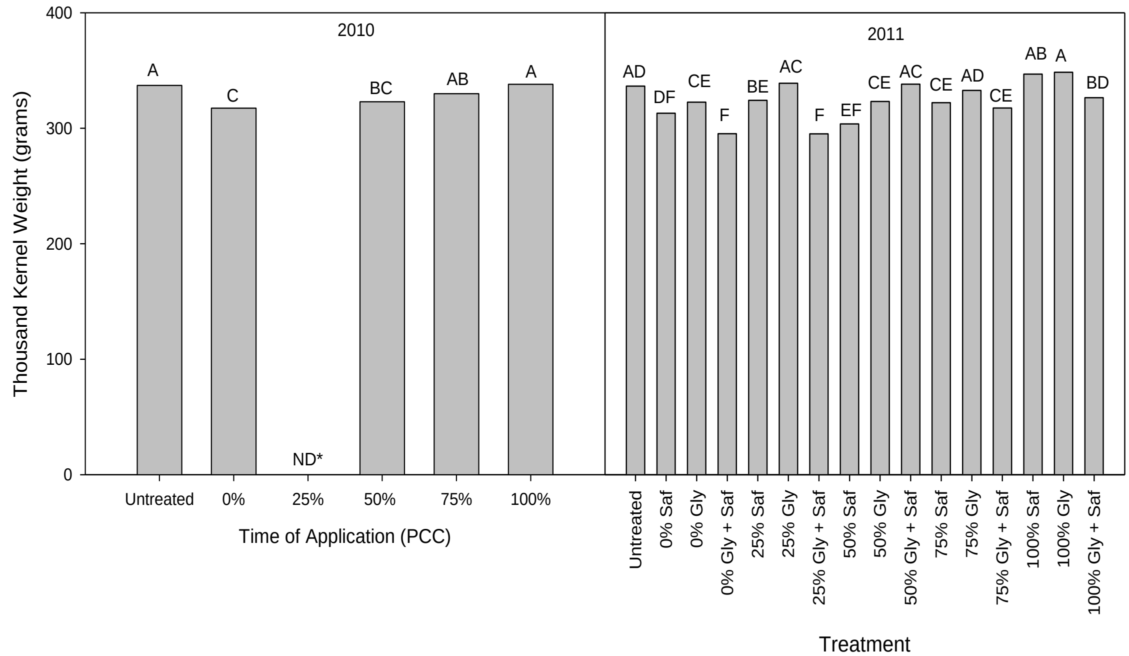

Figure 4.7. The effect of time of herbicide application (2010) and the interaction between herbicide treatment and time of herbicide application (2011) on thousand kernel weight of Pinto bean seed. Treatments applied were saflufenacil alone (Saf), glyphosate alone (Gly) and a glyphosate+saflufenacil mixture (Gly+Saf) at 0%, 25%, 50%, 75% and 100% pod colour change (PCC). No data was collected at the 25% time of application (ND) (refer to Chapter 4.2 Methods and Materials - Section 4.2.5). Within each site-year, means indicated by the same letter are not significantly different according to Fisher's protected LSD at the 0.05 level of significance.

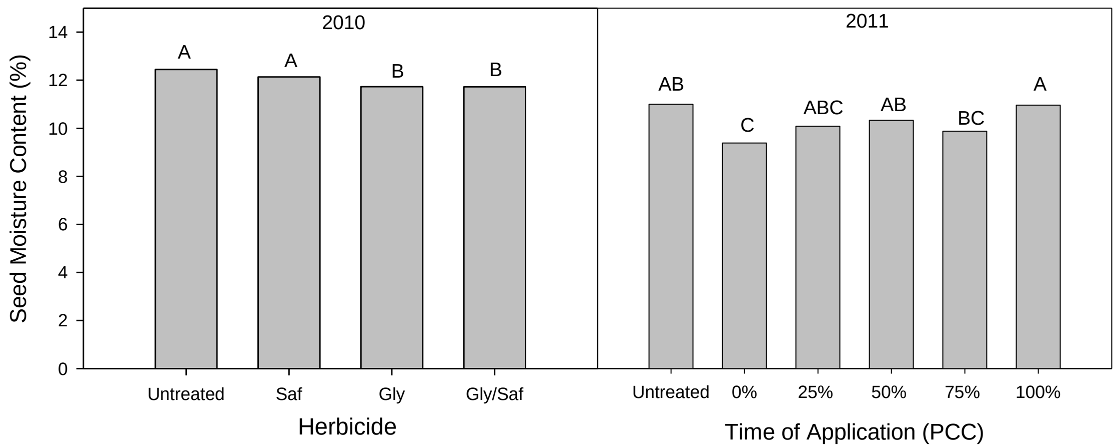

Figure 4.8. The effect of herbicide treatment (2010) and the effect of time of herbicide application (2011) on seed moisture content. Treatments applied were saflufenacil alone (Saf), glyphosate alone (Gly) and a glyphosate+saflufenacil mixture (Gly/Saf) at 0%, 25%, 50%, 75% and 100% pod colour change (PCC). Within each site-year, means indicated by the same letter are not significantly different according to Fisher's protected LSD at the 0.05 level of significance.

4.3.6 Herbicide Residue Analysis

4.3.6.1 Glyphosate Residue

In both site-years, the different harvest aid herbicides applied at the various stages of maturation affected the overall levels of glyphosate residue in Pinto bean seeds. In 2010, glyphosate levels in the seed were affected only by the time of application of the desiccation treatment (Figure 4.9). At the 0% PCC time of application, the level of glyphosate residue found in Pinto bean seed was significantly greater than the glyphosate residue levels found in all other treatments. Glyphosate residue levels in the seed were about 98% lower at the 100% PCC time of application compared to the 0% PCC time of application.

In 2011, glyphosate residue levels in the Pinto bean seed was influenced by an interaction between herbicide treatment and time of application (Figure 4.9). The interaction occurred between the glyphosate alone and the glyphosate+saflufenacil mixture treatments. At the 0% and the 25% PCC times of application, the level of glyphosate residue in Pinto bean seed treated with the glyphosate+saflufenacil mixture was less than the level of glyphosate residue in Pinto bean seed treated with the glyphosate alone. There was no difference in the level of glyphosate residue in Pinto bean seed between the glyphosate alone treatments and the glyphosate+saflufenacil treatments for any other time of application. Glyphosate residue levels in Pinto bean seed were about 99% lower at the 100% PCC time of application for the glyphosate alone and

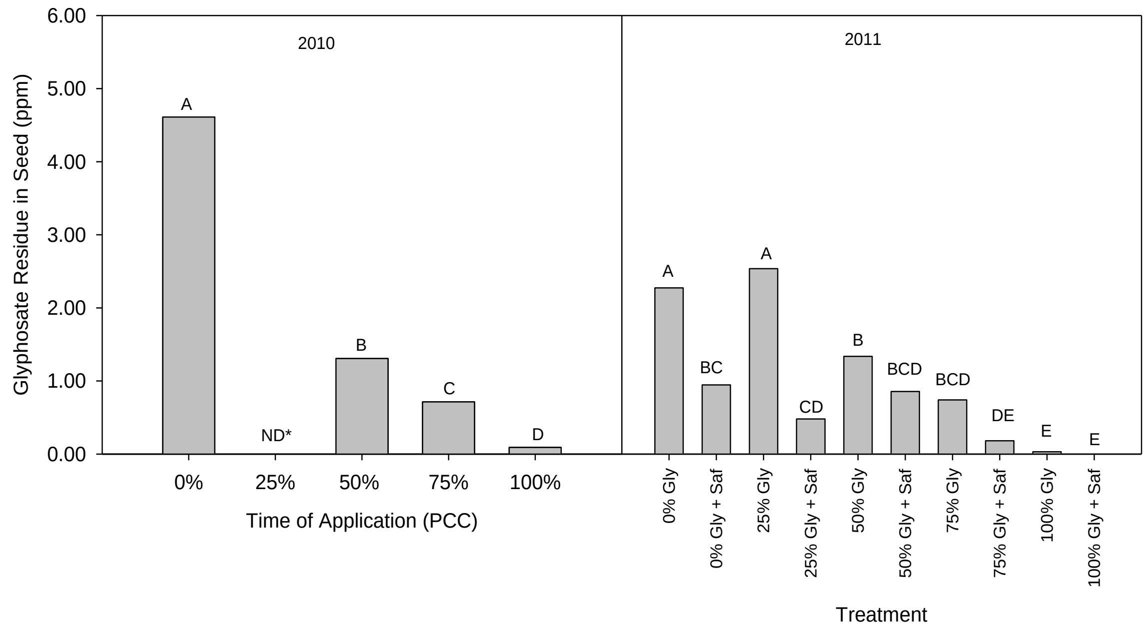

Figure 4.9. The effect of time of herbicide application (2010) and the interaction between herbicide treatment and time of herbicide application (2011) on glyphosate residue in the seed. Treatments applied were saflufenacil alone (Saf), glyphosate alone (Gly) and a glyphosate+saflufenacil mixture (Gly+Saf) at 0%, 25%, 50%, 75% and 100% pod colour change (PCC). No data was collected at the 25% time of application (ND) (refer to Chapter 4.2 Methods and Materials - Section 4.2.5). Within each site-year, means indicated by the same letter are not significantly different according to Fisher’s protected LSD at the 0.05 level of significance.

the glyphosate+saflufenacil mixture treatments compared to the glyphosate alone treatments at the 0% and 25% PCC times of application.

4.3.6.1 Aminomethylphosphonic acid Acid (AMPA) Residue

In both site-years, the different harvest aid herbicides applied at the various timings affected the overall level of AMPA residue in Pinto bean seeds. AMPA residue levels in the Pinto bean seed was affected only by the time of application of the desiccation treatment (Figure 4.10) in 2010. AMPA residue in the Pinto bean seed at the 0% PCC time of application was significantly greater than in all other treatments. There was no difference in AMPA residue levels between the 50% PCC time of application and the 75% PCC time of application. AMPA residue levels in Pinto bean seed were about 88% lower at the 100% PCC time of application compared to the 0% PCC time of application.

The level of AMPA residue in the seed was affected by an interaction between herbicide treatment and time of application (Figure 4.10) in 2011. The interaction occurred between the glyphosate alone and the glyphosate+saflufenacil mixture treatments. At the 0% and the 25% PCC times of application, the level of AMPA residue in Pinto bean seed treated with the glyphosate+saflufenacil mixture were less than the level of AMPA residue in Pinto bean seed that was treated with glyphosate alone. There were no differences in the level of AMPA residues in Pinto bean seed among the glyphosate alone treatments and the glyphosate+saflufenacil treatments for any other time of application. AMPA residue levels in Pinto bean seed were about 88% lower at the 100% PCC time of application for the glyphosate alone and the glyphosate+saflufenacil

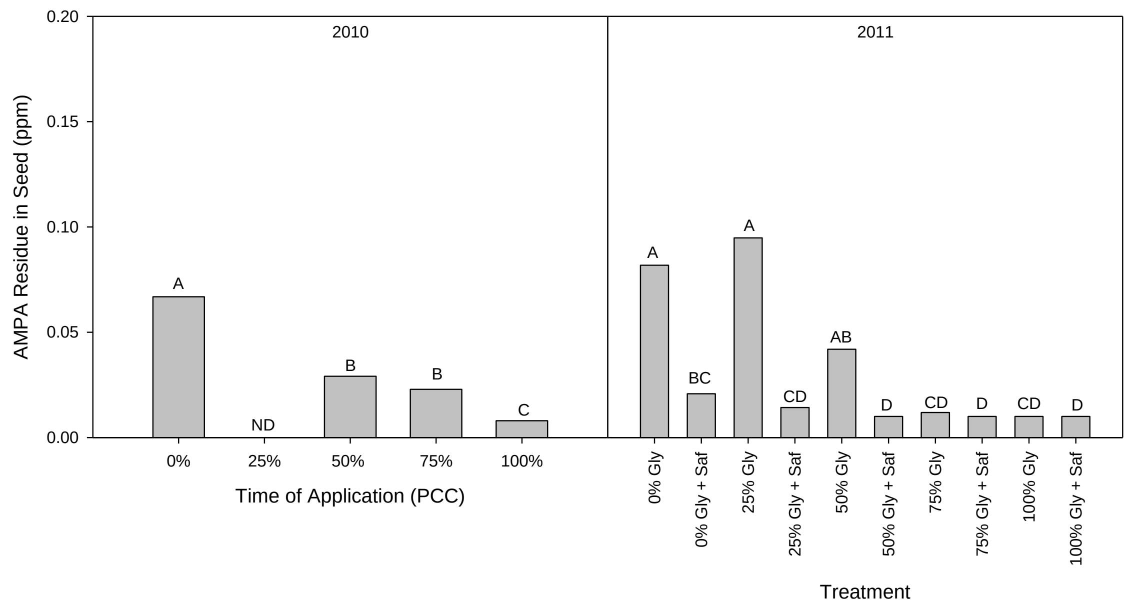

Figure 4.10. The effect of time of herbicide application (2010) and the interaction between herbicide treatment and time of herbicide application (2011) on α-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid (AMPA) residue in Pinto bean seed. Treatments applied were saflufenacil alone (Saf), glyphosate alone (Gly) and a glyphosate+saflufenacil mixture (Gly+Saf) at 0%, 25%, 50%, 75% and 100% pod colour change (PCC). No data was collected at the 25% time of application (ND) (refer to Chapter 4.2 Methods and Materials - Section 4.2.5). Within each site-year, means indicated by the same letter are not significantly different according to Fisher's protected LSD at the 0.05 level of significance.

mixture treatments compared to the glyphosate alone treatments at the 0% and 25% PCC times of application.

4.4 Discussion

Different environmental conditions during maturation of the bean plants in 2010 and 2011 had a large effect on the relative efficacy of the harvest aid herbicides observed within year in this experiment. The cool, wet conditions in 2010, likely contributed to negating the interaction between herbicide treatment and time of application for the residue accumulation of glyphosate and AMPA, bean yield, TKW, seed size, moisture content and stem desiccation. Other studies have concluded that environmental conditions can influence herbicide efficacy by either promoting or inhibiting herbicide uptake and mobility within a plant (Riethmuller-Haage et al. 2007; Skuterud et al. 1998; Stewart et al. 2010; Wilson and Smith 2002). In this study in 2010, slow dry down among all treatments or other factors that may have increased variability within treatments that likely contributed to the lack of an interaction between time of application and herbicide treatment.

Desiccation of the bean plants occurred at variable speeds (due to observed differences in the AUDPC) depending on the applied harvest aid treatment; however, at 16 DAA, all treatments desiccated completely. All harvest aid treatments applied after physiological maturity (80% PCC) of the bean seed had similar speed and efficacy of desiccation which was likely influenced by the contributions of natural senescence of the plants. Due to the slow-acting, systemic nature of glyphosate, all glyphosate alone treatments desiccated bean plants more slowly than plants treated with the faster-acting saflufenacil. This was true for all treatments containing saflufenacil. These results for saflufenacil were similar to a study by Knezevic et al (2009) which showed the addition of saflufenacil to glyphosate can improve the overall efficacy of this mixture on a number of weed species compared to each herbicide applied alone.

The ability to manage glyphosate and AMPA residue in harvested seed is critical when considering the export market for dry beans. Maximum residue limits (MRL) are determined based on international standards to regulate the concentration of pesticide residues in seed (Table 2.1). The European Union (EU) and Japanese markets are the major export markets for Canadian dry beans and have MRLs of 2 parts per million (ppm) for glyphosate and AMPA. In comparison, the Canadian MRLs for glyphosate and AMPA are 4 ppm (Food and Agriculture Organization 2010, Foreign Agricultural Services 2012).

In 2010, the 0% PCC time of application of harvest aid treatments including glyphosate exceeded the Canadian MRL (4 ppm) for glyphosate residue while no other treatments exceeded the Canadian or EU/Japan MRLs that year. In 2011, the addition of saflufenacil to glyphosate appeared to limit the amount of glyphosate that translocated through the plants. In both site-years, as application of harvest aid herbicides approached physiological maturity of dry bean plants, the accumulation of glyphosate and AMPA residues in dry bean seed decreased. When plant seeds approach maturity, movement of assimilates into bean seed is limited and herbicide translocation into the seed ceases (Cessna et al. 2000; 2002). Ashigh and Hall (2010) speculated that the contact activity of saflufenacil causes rapid cell death which limits the ability of the glyphosate to translocate fully throughout the plant. This is consistent with the results found in this study, as in 2011, any treatment that contained the mixture of glyphosate and saflufenacil did not exceed the MRLs for either Canada or EU/Japan for either glyphosate or AMPA residues at any time of application in this study and only the 0% and 25% glyphosate alone treatments exceeded the EU/Japan MRL restriction of 2 ppm. AMPA did not exceed even the lowest MRL at any time of application. Similar results were found in studies by Cessna et al. (2000 and 2002). Although these studies were conducted on different crop species (field pea, barley, flax and canola) they demonstrate that as a crop approaches maturity, the amount of herbicide that is translocated through the plant and into the seed generally decreases. Field pea and flax are indeterminate crops similar to dry bean and when glyphosate was applied at a rate of 900 g ai ha^{-1} to these crops at physiological maturity, glyphosate residues in the seed never exceeded the MRL (5 mg kg^{-1}for pea and 3 mg kg^{-1}for flax) (Cessna et al. 2000; 2002).

The effect of harvest aid herbicides on yield and seed quality (TKW and seed size) was variable depending on the site-year, however, similar trends were observed between the two site-years. As harvest aid treatments were applied closer to physiological maturity, the differences in yield and seed quality became less pronounced among the treatments. These results are consistent with studies previously conducted in dry bean and soybean in response to harvest aid applications and overall post-harvest seed quality (Ratnayake and Shaw 1992; Wilson and Smith 2002). Ratnayake and Shaw (1992) and Wilson and Smith (2002) concluded that herbicide applications made prior to maturity may have adverse effects on final seed yield and quality. For example, if the application of glyphosate was delayed until at least 60% PCC for dry bean and 50% PCC for soybean, no significant yield reductions were observed. Prior to 60% PCC, yield was reduced by up to 63% in dry bean and up to 85% in soybean. Despite statistical significant differences among treatments, biologically, the observed differences among treatments in seed size and TKW in this study were likely of little significance from a producer's perspective.

At harvest, the influence of the main effects on seed moisture content were inconsistent between site-years. In 2010, any application containing glyphosate reduced seed moisture content. The reduction in seed moisture content in the glyphosate alone and glyphosate+saflufenacil mixture treatments were slight compared to the saflufenacil alone and untreated control treatments. In 2011, the seed moisture content may have been influenced by the length of time bean plants remained in the field once complete desiccation was achieved. Some of the treatments to which desiccants were applied at the early stages of maturation would have been ready to be harvested prior to the date on which they were harvested. The low seed moisture contents may have been circumvented by an earlier harvest. Low seed moisture content at the time of harvest leaves Pinto bean seeds more prone to physical damage such as splitting during mechanized harvest. Seeds with a higher moisture content are more likely to withstand physical damage during harvest, thus improving the overall quality of the marketable bean seed (Shahbazi et al.

2011). Research by King and Riddolls ([1962] cited in Bourgeois et al. 1996) indicated that excessively high seed moisture content at the time of harvest can also be of concern due to the potential for physiological damage to the embryo leading to reductions in germinability of seed.

Recent studies by Roskamp and Johnson (2013) and Roskamp et al. (2013) have shown the efficacy of saflufenacil might be influenced by water quality or the addition of herbicides that alter the solution pH. Acidic solutions may reduce the herbicidal efficacy of saflufenacil. This could be a concern when mixing glyphosate and saflufenacil as glyphosate is a weak acid (Grossbard and Atkinson 1997) and has been shown to lower the pH of the solution (Roskamp and Johnson 2013; Roskamp et al 2013). In this study, there were no visible antagonistic effects of mixing glyphosate and saflufenacil. Distilled water from the same source was used as a carrier for all herbicide solutions in both years of the study to eliminate potential confounding effects of water quality.

Based on the results from this experiment the tank-mix of glyphosate+saflufenacil and potentially saflufenacil alone appear to act as an effective harvest aid option for Manitoba producers. Application at a minimum 75% PCC (approximately physiological maturity) provides consistent desiccation and reduces the potential risk of glyphosate accumulation in the seed. There was no residue data collected for saflufenacil in this research so no residue level comparisons can be made in terms of saflufenacil alone treated seed.

4.5 Conclusion

This research has demonstrated that the addition of saflufenacil to glyphosate does not affect seed yield or quality of dry beans when applied as a harvest aid at a development stage near physiological maturity. The mixture of these herbicides appeared to reduce the potential for glyphosate to accumulate in the bean seed, due to the restricted movement of the glyphosate from the fast acting nature of the saflufenacil. No dry beans that were treated with a harvest aid that was applied at or after 75% PCC contained residue levels exceeding MRLs for any major export market.

5.0 EVALUATION OF TANKMIXING CONTACT HERBICIDES WITH TWO RATES OF GLYPHOSATE ON WEED CONTROL AT PRE-HARVEST TIME OF APPLICATION

Abstract. Field experiments were conducted in 2010 and 2011 to determine the effect of different harvest aid herbicides and their tank-mixes with two different doses of glyphosate on weed desiccation. Weeds evaluated were redroot pigweed (*Amaranthus retroflexus* L.), wild buckwheat (*Polygonum convolvulus* L.) and green foxtail (*Setaria viridis* [L.] Beauv.). Treatments of carfentrazone-ethyl, diquat, flumioxazin, glufosinate and saflufenacil alone or in mixture with glyphosate 450 g ai ha^{-1} and glyphosate 900 g ai ha^{-1} were applied to the plots at the physiological maturity stage of dry beans with the majority of the weeds at physiological maturity and beginning to senesce. The addition of glyphosate to any contact herbicide (except diquat) typically improved the speed and desiccation of all plant parts. Treatments containing carfentrazone-ethyl provided the poorest desiccation and overall efficacy of all herbicide treatments. Glufosinate was only improved by the addition of glyphosate in 2011. Overall, the addition of glyphosate at either 450 or 900 g ai ha^{-1} improved the efficacy of the contact harvest aid herbicides for controlling *A. retroflexus, P. convolvulus* and *S. viridis* with a glyphosate and saflufenacil mixture providing the most consistent weed control.

5.1 Introduction

Harvest aid herbicides are used in many crops to provide dry bean producers late season weed control. Late season annual and perennial weeds can decrease the quality of dry beans at harvest by staining the bean surface (due to green tissue or coloured fruit from the weed species) and also interfere with harvest operations (Baig and Gamache 2006; Carvalho and Christoffoleti 2008; Sikkema et al. 2008). Late season annual weeds like *Amaranthus retroflexus*, *Polygonum convolvulus* and *Setaria viridis* are often difficult to control, especially at a mature stage of development (Baig and Gamache 2006; Carvalho and Christoffoleti 2008). All three aforementioned weed species are commonly found in abundance in the majority of fields in Manitoba and across Canada (Douglas et al. 1985; Hume et al. 1983; Weaver and McWilliams 1980).

The ideal harvest aid herbicide for weed control is one that provides rapid dry down of plant tissue, low use rates and contact and systemic activity (Baylis 2000; Soltani et al. 2009). Herbicides currently registered and used by producers for application to dry bean prior to harvest are glyphosate, carfentrazone-ethyl, flumioxazin, glufosinate ammonium and diquat (Anonymous 2013).

Glyphosate provides producers with a herbicide that offers uniform plant death in susceptible crop and weed species, controls plant regrowth effectively and is considered to be the most commonly used herbicide in Canada (Atkinson and Grossbard 1985; Baylis 2000; Franz et al. 1997; Hartzler et al. 2006; Sharma 1986).Glyphosate effectively controls many annual and broadleaf weeds; however, control of some weed species (especially perennial weeds or annuals at a later stage of development) may require a higher dose of glyphosate in order to be controlled (Krausz et al. 1996; Shaw and Arnold 2002). Often in the presence of hard to kill weeds or high weed populations, tank-mixing contact herbicides with glyphosate can improve overall efficacy for weed control (Shaw and Arnold 2002).

The objective of this study was to evaluate new and existing herbicides as possible harvest aids for use in Manitoba dry bean production to determine if they are capable of providing fast, uniform dry down of weeds present prior to harvest timing when in combination with two doses of glyphosate.

5.2 Methods and Materials

5.2.1 Site Establishment

Field experiments were conducted in 2010 and 2011 at the Ian N. Morrison Research farm in Carman, Manitoba. In brief, the experiment site in both years was established in the same manner as outlined in Chapter 3 (page 27).

5.2.2 Experimental Design

This experiment was structured in a randomized complete block design (RCBD) with four replicates. In 2011, the experiment was established twice with an early and a late seeding date. Harvest aid herbicide treatments consisted of glyphosate alone at a dose of 450 and 900 g ai ha^{-1}, diquat alone at a dose of 550 g ai ha^{-1}, glufosinate alone at a dose of 450 g ai ha^{-1}, carfentrazone-ethyl alone at a dose of 28 g ai ha^{-1}, flumioxazin alone at a dose of 71.4 g ai ha^{-1}, saflufenacil alone at a dose of 50 g ai ha^{-1} and each of these contact herbicides at these doses in mixture with glyphosate at a dose of 450 or 900 g ai ha^{-1}. Herbicides doses were based on the recommended and most commonly used rates in the area. Each block contained 17 different herbicide treatments plus an untreated control. Each plot was 3 x 8 meters in size.

5.2.3 Dry Bean Establishment

Dry bean establishment was similar to that outlined in Chapter 3; however, this experiment in 2011 had an additional seeding date. Bean seed was planted at 83 kg ha^{-1} and a row spacing of 75 cm on June 9th, 2010 and June 18th (early seeding date) and June 27th (late seeding date), 2011, using a small plot seeder. Seed was placed at a depth of 2.5 – 3 cm.

5.2.4 Weed Establishment

Native weed populations were chosen based on their density in the field sites each year. The three common species found consistently throughout the plots were *Amaranthus retroflexus* L., *Polygonum convolvulus* L. and *Setaria viridis* (L) Beauv. In 2011, the weed species were found in both early seeded and late seeded plots. Ratings on *A. retroflexus* were collected in both early and late seeded plots while *P. convolvulus* was rated only in the early seeded plot and *S. viridis* only in the late seeded plot.

5.2.5 In-Crop Weed Control

In 2010, in-crop weed control was equivalent to the weed control applications outlined in Chapter 3 until the July 16 herbicide application. Basagran Forte was then applied a second time on August 11 at a dose of 2.275 L ha^{-1} at a carrier (water) volume of 100 L ha^{-1} to set back weed development.

In 2011, initial applications of a grass and a broadleaf herbicide were applied as per indicated in Chapter 3. In addition to these in-crop herbicides, Pursuit herbicide (active ingredient imazemethapyr, 240 g L^{-1}) (Anonymous 2013) was applied July 7 at a dose of 2.0995 L ha^{-1} with a water volume of 100 L ha^{-1}, when the crop was at the 4th trifoliate developmental stage to set back weed development.

5.2.6 Harvest Aid Application

In 2010, harvest aid herbicide treatments were applied at physiological maturity (80% PCC) of the bean seed (Cessna et al. 2002; Wilson and Smith 2002). In 2011 harvest aid treatments were applied prior to the weed species initiating natural senescence. Herbicide treatments are described in Table 5.1.With the inclusion of an untreated control treatment, this totaled to 18 harvest aid herbicide treatments.

Harvest aid herbicides were applied on September 20, 2010 (temperature 11°C, relative humidity 67%, wind WSW 10 km hr^{-1}) and August 4, 2011 (temperature 24°C, relative humidity 71%, wind WNW 12 km hr^{-1}) for the early seeding date and August 10, 2011 (temperature 21°C, relative humidity 69%, wind NW 6 km hr^{-1}) for the later seeding date. All harvest aid herbicides were applied as described in Chapter 3.

5.2.7 Desiccation Ratings

Visual ratings of the desiccation of *A. retroflexus, P. convolvulus* and *S. viridis* were conducted at 4, 8, 12 and 16 days after application of the harvest aid herbicide treatments. Desiccation of the weed species was assessed by percentage plant tissue desiccated to a maximum of 99%, with 99% equal to complete desiccation. These ratings were used to determine speed of desiccation through the use of area under the desiccation progress curve calculations adopted from Wilcoxson et al. (1975).

Table 5.1 Harvest aid herbicide treatments applied at physiological maturity (80% pod colour change) of dry bean

Harvest Aid Herbicide	Rate	Adjuvant	
Untreated Check			
Glyphosate (Weathermax)	450 g ai/ha		
Glyphosate (Weathermax)	900 g ai/ha		
Diquat (Reglone)	550 g ai/ha	AgSurf	(0.1% v/v)
Glufosinate ammonium (Ignite)	450 g ai/ha		
Carfentrazone-ethyl (Aim)	28 g ai/ha	AgSurf	(0.25% v/v)
Flumioxazin (Valtera)	71.4 g ai/ha	MSO	2.5 L/ha
Saflufenacil (Kixor)	50 g ai/ha	Merge	(0.5% v/v)
Glyphosate (Weathermax) Diquat (Reglone)	450 g ai/ha 550 g ai/ha	 AgSurf	 (0.1% v/v)
Glyphosate (Weathermax) Diquat (Reglone)	900 g ai/ha 550 g ai/ha	 AgSurf	 (0.1% v/v)
Glyphosate (Weathermax) Glufosinate ammonium (Ignite)	450 g ai/ha 450 g ai/ha		
Glyphosate (Weathermax) Glufosinate ammonium (Ignite)	900 g ai/ha 450 g ai/ha		
Glyphosate (Weathermax) Carfentrazone-ethyl (Aim)	450 g ai/ha 28 g ai/ha	 AgSurf	 (0.25% v/v)
Glyphosate (Weathermax) Carfentrazone-ethyl (Aim)	900 g ai/ha 28 g ai/ha	 AgSurf	 (0.25% v/v)
Glyphosate (Weathermax) Flumioxazin (Valtera)	450 g ai/ha 71.4 g ai/ha	 MSO	 2.5 L/ha
Glyphosate (Weathermax) Flumioxazin (Valtera)	900 g ai/ha 71.4 g ai/ha	 MSO	 2.5 L/ha
Glyphosate (Weathermax) Saflufenacil (Kixor)	450 g ai/ha 50 g ai/ha	 Merge	 (0.5% v/v)
Glyphosate (Weathermax) Saflufenacil (Kixor)	900 g ai/ha 50 g ai/ha	 Merge	 (0.5% v/v)

5.2.8 Statistical Analysis

The speed of desiccation of Pinto bean plants was calculated and normality of residuals and presence of outliers were determined as described in Chapter 3. When the residuals of response variables did not conform to the normal distribution a different approach of statistical treatment of the data was required. When none of the tested distributions of the GLIMMIX procedure produced a satisfactory result of the chi-square test for dispersion, final mean ratings of 99% desiccation for the 2011 *S. viridis* and *A. retroflexus*$_{late}$ desiccation were removed from the data set due to a lack of variability within these treatments. For response variables where the residuals conformed to the normal distribution, the Mixed procedure was used as described previously (Chapter 3). A one-way treatment structure with herbicide treatment as the fixed effect and replication as the random effect was used. Because the weed spectrum was different for each site-year, the analyses were conducted within site-year and weed species. Following ANOVA, the means were separated as described in Chapter 3.

5.3 Results

5.3.1 Efficacy and Speed of Desiccation

Visual ratings and AUDPC were used to determine the speed and efficacy of each harvest aid herbicide on three different weed species. The weed species investigated were *Amaranthus retroflexus, Polygonum convolvulus* and *Setaria viridis*. With equal final desiccation ratings at 16 DAA of the target weed species, differences in the AUDPCs among the treatments are indicative of the speed of desiccation. When desiccation of the weed species differed among treatments at the final time of rating, differences in the AUDPC may be due to differences in final desiccation rating at 16 DAA, differences in the speed of desiccation, or both.

5.3.1.1 Glyphosate

The application of glyphosate alone did not allow for complete desiccation at 16 DAA for any weed species in 2010 (Table 5.2) and only *A. retroflexus* in 2011 (Table 5.3). Increasing the dose from glyphosate450 to glyphosate900 improved the efficacy of all harvest aid applications significantly for *A. retroflexu*s and *P. convolvulus* in 2010 and 2011.

5.3.1.2 Diquat

The addition of glyphosate to diquat did not improve the speed or efficacy of desiccation at 16 DAA in either site year for any weed species investigated (Table 5.2, Table 5.3). *S. viridis* was not fully desiccated at 16 DAA in 2010 by diquat alone of the diquat900 mixture; however, both treatments were similar to the diquat450 mixture which did exhibit full desiccation. In 2011, similar final desiccation of *S. viridis* by treatments containing diquat led to a similar speed of desiccation. *P. convolvulus* did not fully desiccate with any treatment at 16 DAA in 2011 but final desiccation and AUDPC was consistent among all three treatments containing diquat. All remaining treatments exhibited full desiccation with similar speed of efficacy for *A. retroflexus* and *P.convolvulus*.

5.3.1.3 Glufosinate

Glufosinate was a more effective harvest aid treatment in 2011 (Table 5.3) than 2010 (Table 5.2) in terms of its ability to fully desiccate the different weed species at 16 DAA. In 2010, *P. convolvulus* was the only weed species to reach full desiccation during the 16 day rating period. The addition of glyphosate to glufosinate did not affect the speed or desiccation of any of the three weed species.

In 2011, the addition of glyphosate to glufosinate improved the overall efficacy of desiccation at 16 DAA for *A. retroflexus*$_{early}$, *A. retroflexus*$_{late}$ and *P. convolvulus. S. viridis* reached full desiccation with all glufosinate treatments and was not affected by the addition of glyphosate in 2011.

5.3.1.4 Carfentrazone-ethyl

For all three weed species, the efficacy of carfentrazone-ethyl was improved markedly with the addition of glyphosate in both site years (Table 5.2, Table 5.3), although no differences in speed of desiccation were observed between carfentrazone alone and glyphosate in 2010. In both years, carfentrazone-ethyl applied alone did not result in full desiccation in any of the weed species at 16 days after application. No treatment with carfentrazone-ethyl reached full desiccation for *A. retroflexus* in 2010 or *P. convolvulus* in 2011. Only the carfentrazone900 treatment fully desiccated *P. convolvulus* in 2010 at 16 days after application.

5.3.1.5 Flumioxazin

Applied alone, flumioxazin did not result in complete desiccation in any weed species at 16 DAA. The addition of glyphosate to flumioxazin greatly improved the efficacy of weed control based on final desiccation ratings in both site-years for all three weed species (Table 5.2, Table 5.3). No treatment with flumioxazin resulted in full desiccation of *P. convolvulus* in 2011 and only the flumioxazin900 treatment fully desiccated *A. retroflexus* at 16 DAA in 2010.

5.3.1.6 Saflufenacil

The addition of glyphosate to saflufenacil improved the speed of desiccation and overall efficacy at 16 DAA only for *S. viridis* and *P. convolvulus* (2011) (Table 5.2, Table 5.3). Saflufenacil alone did not fully desiccate *S. viridis* (2010, 2011) or *P. convolvulus* (2011) DAA. Treatments with similar final efficacy exhibited similar speed of desiccation for all weed species with the exception of *A. retroflexus* (2011) where the AUDPC for saflufenacil900 was greater than saflufenacil alone. All remaining treatments exhibited full desiccation with similar speed of efficacy.

Table 5.2 Area under the desiccation progress curve (AUDPC) and desiccation (% Des.) of *Amaranthus retroflexus* , *Polygonum convolvulus* and *Setaria viridis* at 16 days after application in 2010

	Weed Species					
	A. retroflexus		*P. convolvulus*		*S.viridis*	
Treatment	AUDPC	% Des.	AUDPC	% Des.	AUDPC	% Des.
Glyphosate 450	66 *F* [a]	53 *G*	102 *G*	81 *E*	97 *GH*	73* *F*
Glyphosate 900	86 *EF*	65 *EF*	146 *F*	92 *B-D*	119 *FG*	85 *B-F*
Diquat 550	162 *AB*	79 *A-C*	215 *A-D*	95 *A-C*	161 *C-F*	80 *D-F*
Diquat 550/Glyphosate 450	162 *AB*	83 *AB*	237 *A*	98 *A*	189 *A-D*	88 *A-E*
Diquat 550/Glyphosate 900	160 *AB*	85 *A*	232 *AB*	97 *AB*	155 *C-F*	85 *B-F*
Glufosinate 450	119 *B-E*	66 *D-F*	209 *A-D*	96 *A-C*	161 *C-F*	79 *EF*
Glufosinate 450/Glyphosate 450	126 *A-E*	69 *C-F*	196 *B-E*	96 *A-C*	132 *E-G*	84 *B-F*
Glufosinate 450/Glyphosate 900	100 *D-F*	68 *D-F*	202 *A-D*	97 *AB*	139 *D-G*	82 *C-F*
Carfentrazone 28	141 *A-D*	61 *FG*	189 *C-E*	89 *D*	61 *H*	43 *G*
Carfentrazone 28/Glyphosate 450	123 *A-E*	70 *C-F*	162 *EF*	91 *CD*	151 *C-F*	88 *A-E*
Carfentrazone 28/Glyphosate 900	135 *A-D*	74 *B-E*	215 *A-D*	97 *AB*	181 *B-E*	92 *A-D*
Flumioxazin 71.4	106 *C-F*	61 *FG*	185 *DE*	92 *B-D*	134 *E-G*	80 *D-F*
Flumioxazin 71.4/Glyphosate 450	98 *D-F*	65 *EF*	194 *C-E*	96 *A-C*	195 *A-C*	95 *A-C*
Flumioxazin 71.4/Glyphosate 900	147 *A-C*	80 *A-C*	214 *A-D*	99 *A*	216 *AB*	99 *A*
Saflufenacil 50	141 *A-D*	78 *A-D*	214 *A-D*	95 *A-C*	142 *D-G*	74 *F*
Saflufenacil 50/Glyphosate 450	161 *AB*	83 *AB*	223 *A-C*	98 *A*	222 *AB*	97 *AB*
Saflufenacil 50/Glyphosate 900	165 *A*	83 *AB*	220 *A-D*	98 *A*	254 *A*	96 *A-C*

[a]Within columns, means followed by the same letter are not significantly different according to Fisher's protected LSD at the 0.05 level of significance. If there is no letter present, means are not significantly different.

*indicates desiccation ratings were tested using Proc GLIMMIX (Poisson distribution, identity link)

Table 5.3 Area under the desiccation progress curve (AUDPC) and desiccation (% Des.) of *Amaranthus retroflexus* (early and late seeding , *Polygonum convolvulus* and *Setaria viridis* at 16 days after application (DAA) in 2011

	Weed Species							
	A. retroflexus $_{early}$		*A. retroflexus* $_{late}$		*P. convolvulus*		*S.viridis*	
Treatment	AUDPC	% Des.	AUDPC	% Des.	AUDPC	% Des.	AUDPC	% Des.
Glyphosate 450	131 *I*[a]	71 *C*	208 *F*	94 *AB*	86 *H*	45 *E*	237 *F*	96 *A*
Glyphosate 900	155 *H*	86 *AB*	225 *EF*	99 *	97 *GH*	60 *CD*	260 *DE*	99 *
Diquat 550	236 *AB*	90 *AB*	241 *C-E*	94 *AB*	195 *B-E*	71 *C*	271 *B-D*	99 *
Diquat 550/Glyphosate 450	243 *A*	86 *AB*	247 *C-E*	91 *AB*	211 *BC*	75 *C*	281 *AB*	99 *
Diquat 550/Glyphosate 900	232 *A-C*	88 *AB*	249 *B-E*	97 *A*	191 *C-E*	76 *C*	269 *B-E*	98 *A*
Glufosinate 450	196 *E-G*	81 *BC*	229 *D-F*	87 *B*	181 *DE*	80 *BC*	267 *B-E*	99 *
Glufosinate 450/Glyphosate 450	196 *E-G*	84 *AB*	247 *C-E*	96 *AB*	208 *BC*	88 *AB*	275 *A-D*	99 *
Glufosinate 450/Glyphosate 900	210 *D-F*	89 *AB*	235 *DE*	98 *A*	211 *A-C*	89 *AB*	267 *B-E*	99 *
Carfentrazone 28	118 *I*	53 *D*	104 *H*	40 *D*	92 *GH*	39 *E*	74 *H*	31 *D*
Carfentrazone 28/Glyphosate 450	189 *G*	84 *AB*	234 *DE*	97 *A*	146 *F*	61 *D*	256 *E*	99 *
Carfentrazone 28/Glyphosate 900	237 *AB*	85 *AB*	252 *A-D*	98 *A*	179 *E*	74 *C*	264 *C-E*	99 *
Flumioxazin 71.4	158 *H*	53 *D*	146 *G*	54 *C*	118 *G*	46 *E*	173 *G*	64 *C*
Flumioxazin 71.4/Glyphosate 450	190 *FG*	84 *AB*	251 *A-D*	99 *	179 *E*	71 *C*	269 *B-E*	99 *
Flumioxazin 71.4/Glyphosate 900	222 *B-D*	89 *AB*	263 *A-C*	99 *	206 *B-D*	80 *BC*	277 *A-C*	99 *
Saflufenacil 50	212 *C-E*	85 *AB*	228 *D-F*	89 *AB*	214 *A-C*	80 *BC*	223 *F*	88 *B*
Saflufenacil 50/Glyphosate 450	226 *A-D*	93 *A*	273 *AB*	99 *	219 *AB*	90 *A*	277 *A-C*	99 *
Saflufenacil 50/Glyphosate 900	238 *AB*	91 *AB*	274 *A*	99 *	237 *A*	88 *AB*	287 *A*	99 *

a Within columns, means followed by the same letter are not significantly different according to Fisher's protected LSD at the 0.05 level of significance. If there is no letter present, means are not significantly different.

*indicates treatments with final mean ratings of 99% desiccation were not included in included in statistical analysis due to a lack of variation among the replicates

5.3.2 Alternative Harvest Aid Herbicides Applied Alone in Comparison with Diquat

The efficacy of harvest aid herbicides applied alone had variable effects on the desiccation of *A. retroflexus, P. convulvulus* and *S. viridis* when compared to the traditional, standard harvest aid herbicide, diquat. Diquat alone exhibited either equal to or greater overall efficacy of desiccation in comparison to all other herbicide applied alone to all three weed species in both site-years of this study (Table 5.2, Table 5.3).

Amaranthus retroflexus. Diquat alone always desiccated *A. retroflexus* greater than carfentrazone-ethyl alone or flumioxazin alone based on final efficacy. In 2010, diquat alone also exhibited greater efficacy than glufosinate alone at 16 DAA. Glufosinate alone and saflufenacil alone exhibited a slower speed of desiccation than diquat alone for *A. retroflexus*$_{early}$ in 2011 at 16 DAA.

Polygonum convolvulus. Diquat alone always resulted in greater efficacy of desiccation of *P. convolvulus* at 16 DAA than carfentrazone-ethyl alone and in 2011, final efficacy of diquat alone was also greater than flumioxazin alone. In 2010, flumioxazin alone exhibited a slower speed of desiccation that diquat alone for *P. convolvulus* at 16 DAA.

Setaria viridis. Similar to previous weed species, diquat alone always desiccated *S. viridis* greater than carfentrazone-ethyl alone based on final efficacy at 16 DAA. In 2011, diquat alone also desiccated *S. viridis* greater than flumioxazin alone and saflufenacil alone at 16 DAA.

5.4 Discussion

Similar to observations on bean plants discussed in Chapter 3, environmental conditions contributed greatly to the relative efficacy of the different harvest aid herbicides on weeds between the two years in this study. In 2010, the weeds under investigation were closer to maturity than in 2011, and thus were more difficult to desiccate due to plant size, plant maturity, and cool environmental conditions at the time of herbicide application. In 2011, warmer temperatures were ideal for harvest aid application and provided optimal conditions for rapid desiccation of the weeds.

Weed control in this study was not as consistent among the herbicides and study years as expected. Herbicide efficacy for weed control seemed to be dependent on the weed species, herbicide applied and the year of application. The efficacy and uptake of a foliar herbicide application is dependent on plant species, developmental stage of the weed species and the environmental conditions at the time of application (Caseley 1963; Hammerton 1967; Riethmuller et al. 2007; Wang and Liu 2007). In 2010, the harvest aid herbicide treatments were applied when the Pinto bean plants had reached physiological maturity and the weed species had already begun to senesce. The timing of the harvest aid application was well beyond the recommended application guidelines for control of the three weed species as outlined by the Manitoba Guide to Field Crop Protection

(Anonymous 2013) for the harvest aids under review. This late time of application and advanced development of the weed species at the time of application of the harvest aid herbicides likely contributed to the lack of acceptable control by many of the treatments. Harvest aid herbicides were applied at a less mature stage of development of the target weed species in 2011, prior to the onset of senescence of the weed species.

The three weed species had three distinct growth habits that likely contributed to the uptake and efficacy of the harvest aid herbicides applied. *Polygonum convolvulus* is an annual dicot weed that exhibits a vining, creeping growth habit and requires adequate coverage of the leaf surface in order to be effectively controlled by a herbicide application (Bryson and DeFelice 2010; Hume et al. 1983 Royer and Dickinson 1999). *P. convolvulus* tends to “climb” taller plants through use of the plant tendrils in order to gain access to sunlight for development (Hume et al. 1983). Control of *P. convolvulus* was acceptable for all of the harvest aid herbicide treatments applied with the exception of glyphosate450, carfentrazone alone and carfentrazone450 in 2010 and only acceptable for glufosinate/glyphosate mixtures and saflufenacil/glyphosate mixtures in 2011. The poor control with these treatments was likely due to the inability of the aforementioned herbicide treatments to provide adequate coverage the leaf surfaces of *P. convulvulus* or the ability of the herbicides to be taken up and translocated throughout the plant. A study by Sandberg et al. (1980) also demonstrated that glyphosate tends to exhibit a low level of absorption and translocation in *P. convolvulus.*

Amaranthus retroflexus is also an annual dicot and exhibits an indeterminate, erect growth habit (Bryson and DeFelice 2010; Royer and Dickinson 1999). Due to the amount of plant tissue produced by this weed species it was best controlled by a mixture of herbicides that exhibited systemic and contact activity. In 2010, herbicide efficacy was best realized with treatments containing diquat or saflufenacil. In 2011, most treatments were considered successful in controlling *A. retroflexus*, likely due to the ideal environmental conditions (warm temperatures, humid conditions) at the time of herbicide application and the less mature stage of development of *A. retroflexus*.

Setaria viridis is an annual grass species that is a prolific seed producer and will germinate whenever conditions are favorable throughout the growing season (Bryson and DeFelice 2010; Royer and Dickinson 1999). *Setaria viridis* exhibits C4 photosynthesis and growth of this weed species is promoted by warm, dry conditions with ample available light (Bryson and DeFelice 2010; Royer and Dickinson 1999). Since environmental conditions were not favorable for germination early in the 2010 growing season, *S. viridis* appeared to emerge markedly later than the other weed species in the study resulting in this weed species predominantly occupying the understory of the canopy. Due to poor environmental conditions and a heavy population of other, taller weed species at the time of herbicide application, adequate coverage of *S. viridis* was likely not achieved and this contributed to poor overall weed control of this species by most of the contact herbicides. Treatments that were in mixture with glyphosate tended to exhibit a greater level of efficacy, supporting the notion of poor coverage by contact herbicides. Improved efficacy in 2011 was observed due to a) stage of weed species at time of application, b) time of application (earlier in growing season) and/or c) more favourable weather conditions for herbicide application and activity.

Weed control at the time of harvest aid application was variable depending on the weed species and the harvest aid herbicide applied. Ideally, this time of application would not be the optimal stage for weed control in a cropping system as the weeds typically emerge at a similar time as the crop (or shortly after) so at this late stage of development they may be difficult to fully control with harvest aid herbicides. It is possible that perhaps the poor efficacy of some of these herbicides on the weed species in this study could be attributed to the late developmental stage of the weed species under which they were applied. Based on this experiment, the most consistent harvest aid herbicide was saflufenacil in mixture with glyphosate. There were no differences in efficacy or speed of efficacy of weed control in either site-year with this mixture for any weed species under examination.

5.5 Conclusion

This research has demonstrated that the addition of a contact herbicide to glyphosate may improve the level of weed control for certain weed species present at the time of harvest aid application in dry beans. Some contact herbicides were more effective than others at drying down the plant tissue of the three weed species investigated. It is important to remember however, that herbicides that are recommended for control of weed species may have limitations as a harvest aid herbicide due to the difference in time of application and weed size. This information can be used by producers to aid in choosing a harvest aid herbicide for use in their dry bean crops. By determining an appropriate contact herbicide for use in mixture with glyphosate producers have the ability to manage the quality of their dry bean crop through weed control and desiccation of the plant tissue of the dry beans. Further research considering different weed species is warranted based on the findings of this experiment. Shortcomings of this research was that there was a limited weed spectrum investigated and there were only two site-years of data collected, with both site-years conducted at the same location.

6.0 GENERAL DISCUSSION

The preceding experiments were designed to evaluate the efficacy of different herbicides to facilitate desiccation of beans and weeds while reducing glyphosate residue levels in the seed, control weeds present at time of desiccation and to maintain seed quality; for potential use in Manitoba dry bean production. Overall, these experiments demonstrated that diquat, glufosinate and saflufenacil in mixture with glyphosate provided the most consistent results for preventing glyphosate residue accumulation in dry bean seed while facilitating desiccation and providing weed control.

The addition of diquat, flumioxazin, glufosinate and saflufenacil to glyphosate effectively reduced the risk of the translocation and accumulation of glyphosate and its metabolite, AMPA, in dry bean seed when applied at or close to physiological maturity of bean plants. Other contact herbicides (carfentrazone-ethyl) were less efficacious in terms of desiccation and preventing glyphosate residue accumulation. When mixed with glyphosate; diquat (current market standard for desiccation of dry beans), flumioxazin and saflufenacil all provided adequate desiccation of the bean stems, leaves and pods and provided yield, seed size, thousand kernel weight and moisture contents similar to those of the untreated control. Glyphosate residues in bean seed treated with glyphosate/diquat, glyphosate/flumioxazin or glyphosate/saflufenacil were reduced by approximately 20-30% in 2010 and 40-60% in 2011; compared to the glyphosate alone treated seed (Chapter 3). This difference in residue level was not statistically different among treatments; however, it was often the difference between exceeding the maximum residue limit and remaining below the allowable 2 ppm.

Weed control was also improved with the addition of certain contact herbicides to two different doses of glyphosate. The harvest aid herbicides that provided the most consistent efficacy when in mixture with glyphosate at a recommended dose and a reduced dose were diquat, saflufenacil and glufosinate. These harvest aid herbicides provided enhanced, improved control over an application of glyphosate alone at either dose. When using a contact herbicide for weed control, adequate coverage of the plant surface is required for best results (Mersey et al. 1990; Retzlaff 2004; Zagonal 2011).

Time of application of harvest aid herbicides had a major influence on residue accumulation of glyphosate and its metabolite, AMPA in dry bean seed. As plants approached physiological maturity, glyphosate residues were significantly reduced when dry bean was treated with glyphosate mixed with saflufenacil and herbicide treatments (alone or in mixture) were applied after 50% PCC. When harvest aid treatments included a herbicide mixture or treatment was applied at a stage of development of 50% PCC or greater, no treatment exceeded the accepted maximum residue level of 2 ppm. The effect of the glyphosate and saflufenacil mixture is consistent with results from experiments conducted by Ashigh and Hall (2010) and Jordan et al. (1997).

6.1 Future Research

Based on the findings from this research, it is likely that additional contact herbicides would be as equally effective as saflufenacil in providing adequate desiccation while reducing the potential for glyphosate residues to accumulate in dry bean seed at 75% PCC. Diquat, flumioxazin and glufosinate would likely provide similar efficacy for desiccation while maintaining overall seed quality at a stage of development just prior to physiological maturity. Additional research into the specific process of how the contact herbicides inhibit glyphosate movement through the plant would provide insight into what specific properties of a contact herbicide make for an ideal mixture with glyphosate for desiccation. Also, investigating whether a lower rate of glyphosate could be used in mixture with a contact herbicide and still be effective as a harvest aid would be a helpful tool for producers. A lower rate of glyphosate being applied could help further reduce the risk of glyphosate accumulation.

At this time, this research focuses primarily on few market classes of dry beans. Two other market classes (Navy and Cranberry beans) in addition to Pinto beans were investigated using the same experimental design concurrently to these experiments. Future research should expand the number of market classes investigated, and additional different herbicide groups. This could potentially reduce the dependency of the industry on glyphosate for harvest aid application. In addition to different market classes of dry beans, this research could be applied to other pulse species as well. Lentils, faba beans, chick peas and edible peas are crops with increasing importance across the Prairies when considering crop diversification. Current harvest aid practices in these crops are similar to dry beans with glyphosate and diquat being the options available for producers (Anonymous 2013b; Riethmuller et al. 1999).

Future research into harvest aid herbicides could include developing a model to aid in determining physiological maturity of dry bean crops. This tool, if executed properly, would provide a management tool that would ensure that the risk of harvest aid herbicide accumulation in the seed would be minimized. Once produced, this model could be an educational management tool for producers that would be utilized in crop, prior to harvest aid herbicide application. A time of application decision model could also be expanded to other pulse crops as well. Growth habit would have to be taken into consideration and the model adjusted accordingly based on an indeterminate or determinate growth habit.

7.0 LITERATURE CITED

Adams M.W. 1967. Basis of Yield Component Compensation in Crop Plants with Special Reference to the Field Bean *Phaseolus vulgaris*. Crop Sci. 7:505-510

Anonymous. 2000a. Average annual snowfall. Government of Manitoba [online] http://www.gov.mb.ca/ctt/invest/busfacts/qu_oflife/ql_snowfall.html [accessed March 11, 2010]

Anonymous. 2000b. Chapter 9 – Dry Beans. Pulse production manual. 2nd ed. Saskatchewan Pulse Growers, Saskatoon, SK [online] http://www.archive.saskpulse.com/media/pdfs/ppm-dry-bean.pdf [accessed July 12 2013]

Anonymous. 2001. Crop Suitability of Pinto Beans. Static Map Library. Manitoba Agricultural Services Corporation. [online] http://www.mmpp.com/mmpp.nsf/mmpp_static_maps.html [accessed March 13, 2010]

Anonymous. 2002 Commodities: Field Beans. Government of Manitoba. [online] http://www.gov.mb.ca/trade/globaltrade/agrifood/commodity/field_beans.html [accessed March 1, 2010]

Anonymous. 2005. Backgrounder: History of Monsanto's Glyphosate Herbicides. http://www.monsanto.com/monsanto/content/products/productivity/roundup/back_history.pdf [accessed April 19, 2010]

Anonymous 2006. Field Bean Production Guide. Manitoba Agriculture, Food and Rural Initiatives.[online] http://www.gov.mb.ca/agriculture/crops/pulsecrops/bhd03s01.html [accessed May 31, 2013]

Anonymous. 2008. Kixor™ Herbicide, Worldwide Technical Brochure. BASF Publication no/ GL-69288. Research Triangle Park, NC: BASF Corporation. 18 pages.

Anonymous. 2009a. Overview of the Canadian Pulse Industry Agriculture and Agri-Food Canada. [online] http://www.ats.agr.gc.ca/can/pdf/4753-eng.pdf [accessed November 2, 2012]

Anonymous. 2009b. Pesticide Fact Sheet: Saflufenacil. Office of Prevention, Pesticides and Toxic Substances. Environmental Protection Agency. [online] http://www.epa.gov/opp00001/chem_search/reg_actions/registration/fs_PC-118203_01-Aug-09.pdf [accessed June 15 2013]

Anonymous. 2010a. Liberty 150. Bayer CropScience. [online] http://www.bayercropscience.ca/products/herbicides/liberty-150/ [accessed April 2, 2010]

Anonymous. 2010b. Reglone Desiccant Label. Syngenta Crop Protection. [Online] http://www.syngenta.ca/PDF/Labels/REGLONE_26396_en_pamphlet.pdf [accessed April 7, 2010]

Anonymous. 2010c. Monsanto Company History. [Online] http://www.monsanto.com/who_we_are/history.asp [accessed April 7, 2010]

Anonymous. 2011a. Herbicide Resistance Management Lesson II. Weed Science Society of America. [Online] http://www.cottoninc.com/fiber/AgriculturalDisciplines/Weed-Management/training-herbicide-resistant/Lesson-2-How-Herbicides-Work.pdf [accessed September 26 2012]

Anonymous. 2011b. Ignite SN. Bayer CropScience. [Online] http://www.bayercropscience.ca/English/LabelMSDS/227/File.ashx [accessed August 17, 2011]

Anonymous. 2012a. Aim Herbicide Label. [online] http://www.cdms.net/ldat/ldAJL000.pdf [accessed April 20, 2013]

Anonymous. 2012b. Roundup WeatherMAX Herbicide Label. [online] http://roundup.ca/_uploads/documents/27487_Approved_E_Label_06Sep2012_All_uses.pdf [accessed April 20, 2013]

Anonymous. 2013. Guide to Field Crop Protection. Manitoba Agriculture and Rural Initiatives. [online] http://www.gov.mb.ca/agriculture/crops/cropproduction/gaa01d01.html [accessed on April 20, 2013]

Anonymous. 2013a. Pulses in Manitoba. Manitoba Pulse Growers Association. [online] http://www.manitobapulse.ca/for-producers/pulses-in-manitoba/ [accessed September 8, 2013]

Anonymous 2013b. Varieties & Management - Growing Pulse Crops in Alberta. Alberta Pulse Growers. [online] http://www.pulse.ab.ca/producers/varieties-management/lentils/swathing-desiccation [accessed September 5, 2013]

Archer, T.E., J.D. Stokes. 1984. Residue Analysis of Glyphosate in Blackberries by High Performance Liquid Chromatography and Postcolumn Reaction Detection. J. Agric. Food Chem. 32: 586-588

Ashigh, J., J.C. Hall. 2010. Bases for Interaction between Saflufenacil and Glyphosate in Plants. J. Agric. Food Chem. 58:7335-7343

Atkinson, E., D. Grossbard. 1985. The Herbicide Glyphosate. Toronto: Butterworths. 489 pages

Azlin, W.R., C.G. McWhorter. 1981. Preharvest Effects of Applying Glyphosate to Soybeans (*Glycine max*). Weed Sci. 29:123-127

Baig, M. N., A.L. Darwent, K.N. Harker, J.T. Donovan. 2003. Preharvest Applications of Glyphosate affect Emergence and Seedling Growth of Field Pea (*Pisum sativum*) Weed Tech. 17:655-665

Baig, M. N., P. Gamanche. 2006. Pre-Harvest application of glyphosate for Weed Control and Harvest Management. [online] http://www.reducedtillage.ca/article348.aspx [accessed July 12 2013]

Baumann, P.A., P.A. Dotray, E.P. Prostko. 2008. Herbicides: How They Work and the Symptoms They Cause. Texas A&M University. [online] http : / /hdl .handle .net /1969 .1 /86804. [accessed November 21, 2012]

Baylis, A.D. 2000. Why glyphosate is a global herbicide: strengths, weaknesses and prospects. Pest Manag Sci. 56:299-308

Blackshaw, R.E., H.H. Muendel, G. Saindon. 1999. Canopy Architecture, Row Spacing and Plant Density Effects on Yield of Dry Bean (*Phaseolus vulgaris*) in the Absence and Presence of Hairy Nightshade (*Solanum sarrachoides*). Can. J. Plant Sci. 79: 663-669

Blackshaw, R.E., L.J. Molnar, H.H. Muendel, G. Saindon, X. Li. 2000. Integration of Cropping Practices and Herbicides Improves Weed Management in Dry Bean (*Phaseolus vulgaris*). Weed Tech. 14-327-336

Blackshaw, R.E., L.J. Molnar, G.W. Clayton, K.N. Harker, T. Entz. 2007. Dry Bean Production in Zero and Conventional Tillage. Agron. J. 99:122-126

Borggaard, O.K., A.L. Gimsing. 2008. Fate of Glyphosate in Soil and the Possibility of Leaching to Ground and Surface Waters: a Review. Pest Manag Sci. 64:441-456

Brereton J.C., M. McGowan, T.C.K. Dawkins. 1986. The relative sensitivity of spring barley, spring field beans and sugar beet crops to soil compaction. Field Crops Res. 13: 223-237

Bryson, C. T., M.S. DeFelice (Eds). 2010. Weeds of the Midwestern United States and Central Canada. Athens, Georgia: University of Georgia Press. 440 pages

Buhler, D.D., O.C. Burnside. 1983. Effect of water quality, carrier volume, and acid on glyphosate phytotoxicity. Weed Sci. 31:163-169

Burnside, O.C., W.H. Ahrens, B.J. Holder, M.J. Wiens, M.M. Johnson, E.A. Ristau. 1994. Efficacy and economics of various mechanical plus chemical weed control systems in dry beans (*Phaseolus vulgaris)*. Weed Tech. 8: 238-244

Carvalho, S., P.J. Christoffoleti. 2008. Competition of *Amanranthus* Species with Dry Bean Plants. Sci. Agri. 65: 239-245

Caseley, J. 1963. The Effect of Weather on Herbicide Performance. EPPO Bull. 13:171-176

Cerdiera, A.L., S.O. Duke. 2006. The Current Status and Environmental Impact of Glyphosate-Resistant Crops: a Review. J. Environ. Qual. 35:1633-1658

Cerdiera, A.L., S.O. Duke. 2010. Effects of Glyphosate-Resistant Crops on Soil and Water Quality. GM Crops. 1:16-24

Cerkauskas, R.F., O.D. Dhingra, J.B. Sinclair, S.R. Foor. 1982. Effect of three desiccant Herbicides on Soybean (*Glycine max*) seed quality. Weed Sci. 30:484-490

Cessna, A.J., A.L. Darwent, L. Townley-Smith, K.N. Harker, K.J. Kirkland. 2000. Residues of Glyphosate and its Metabolite AMPA in Canola Seed Following Preharvest Applications. Can. J. Plant Sci. 80:425-4431

Cessna, A.J., A.L. Darwent, L. Townley-Smith, K.N. Harker, K.J. Kirkland. 2002. Residues of Glyphosate and its Metabolite AMPA in Field Pea, Barley and Flax Seed Following Preharvest Applications. Can. J. Plant Sci. 82:485-489

Clark, D.G., E.W. Hurst. 1970. The Toxicity of Diquat. Brit. Jou. of Ind. Med. 27:51-55

Clayton, G.W., K.N. Harker, J.T. O'Donovan, M.N. Baig, M.J. Kidnie. 2002. Glyphosate Timing and Tillage System Effects on Glyphosate-Resistant Canola (*Brassica napus*). Weed Tech. 16:124-130

Cobb, A.H., J.P.H. Reade (Eds). 2010. Herbicides and Plant Physiology. 2nd Edition. West Sussex – United Kingdom: Wiley Blackwell. 286 pages.

Coetzer, E., K. Al-Khatib, T.M. Loughin. 2001. Glufosinate efficacy, absorption and translocation in amaranth as affected by relative humidity and temperature. Weed Sci. 49:8-13

Croshney, J.F.H. 1961. A review of experimental work with diquat and related compounds. Weed Res. 1:68-77

Dale, J.E. 1964. Leaf Growth in *Phaseolus vulgaris*. 1. Growth of the first paid of leaves under constant conditions. Ann. of Bot. 28: 579-589

Dayan, F.E., S.O. Duke, J.D. Weete, H.G. Hancock. 1997. Selectivity and Mode of Action of Carfentrazone-ethyl, a novel Phenyl Triazolinone Herbicide. Pest. Sci 51: 65-73

Dayan, F.E., S.O. Duke, K. Grossman. 2010. Herbicides as Probes in Plant Biology, Weed Sci. 58:340-350

Delgado, M.J., F. Ligero, C. Lluch. 1993. Effects of salt stress on growth and nitrogen fixation by pea, faba bean, common bean and soybean plants. Soil Biol. Biochem. 26: 371-376

Devine, M.D. 2005. Why are there not more herbicide tolerant crops? Pest Manag Sci. 61:312-317

Dinham, B. 1996. Paraquat Fact Sheet. Pesticide News: publication No. 32. Pesticide Action Network, United Kingdom. P 20-21 [online] http://www.pan-uk.org/pestnews/Actives/paraquat.htm [accessed March 25, 2010]

Douglas, B.J., A.G. Thomas, I. N. Morrison, M.G. Maw. 1985. The Biology of Canadian Weeds . 70. *Setaria viridis.* Can. J. Plant Sci. 65: 669-690

Duke, S.O., J. Lydon, J.M. Becerril, T.D. Sherman, L.P. Lehnen, H. Matsumoto. 1991. Protoporphyrinogen Oxidase-Inhibiting Herbicides. Weed Sci. 39: 465-473

Duke, S.O., S.R. Baerson, A.M. Rimando. 2003. Glyphosate. Encyclopedia of Agrochemicals. Vol 2. 1638 pages

Duke, S.O., S.B. Powles. 2008. Glyphosate: a once in a century herbicide. Pest Manag. Sci. 64:319-325

Fageria, N.K., A.B. Santos. 2008. Yield Physiology of Dry Bean. Jour. of Pl. Nut. 31: 983-1004

Food and Health Organization 2010. Codex Alimentarius. [online] http://www.codexalimentarius.net/pestres/data/pesticides/details.html?id=158 [accessed October 8, 2012]

Food and Agriculture Organization 2013. Food and Agricultural Commodities Production. [online] http://faostat.fao.org/site/339/default.aspx [accessed May 31, 2013]

Foreign Agricultural Service. 2012. Pesticide MRL Database. [online] http://www.mrldatabase.com/results.cfm [October 22, 2012]

Franz, J.E., M.K. Mao, J.A. Sikorski. 1997. Glyphosate: A Unique Global Herbicide (Acs Monograph). New York: An American Chemical Society Publication. 653 pages

Gates, R.R. 1951. Epigeal Germination in the Leguminosae. Bot. Gazette. 113: 151-157

Gepts, P. 1998. Origin and Evolution of Common Bean: Past events and recent trends. Hort Sci. 33:1124-1130

Gianessi, L.P., M.B. Marcelli. 2000. Pesticide use in the U.S. Crop Production: 1997. National Center for Food and Agricultural Policy, Washington, DC, USA. [online] http://www.ncfap.org/documents/nationalsummary1997.pdf [accessed June 2, 2013]

Goodwin, M. 2003. Crop Profile for Beans. Pulse Canada [online] http://www.pulsecanada.com/uploads/GI/99/GI99nUpdjJyY0jVnwlZ5OA/Bean-Profile.PDF [accessed October 22, 2012]

Graham, P.H., P. Ranalli. 1997. Common bean (*Phaseolus vulgaris* L.). Field Crops Res. 53: 131-146

Granby, K., S. Johannesen, M. Vahl. 2003. Analysis of Glyphosate Residues in Cereals using Liquid Chromatography-mass Spectrometry. Food Add. and Cont. 20: 692-698

Gressel, J. 1987. Appearance of single and multi-group herbicide resistances, and strategies for their prevention. Br. Crop Prot. Conf. - Weeds 2: 479-488.

Griffin, J.L., J.M. Boudreaux, D.K. Miller. 2010. Herbicides as Harvest aids. Weed Sci. 58: 355-358

Grossman, K., R. Niggewig, N. Christiansen, R. Looser, T. Ehrhardt. 2010. The Herbicide Saflufenacil (Kixor™) is a New Inhibitor of Protoporphyrinogen IX Oxidase Activity. Weed Sci. 58:1-9

Grossman, K., J. Hutzler, G. Caspar, J. Kwiatkowski, C.L. Brommer. 2011. Saflufenacil (Kixor™): Biokinetic Properties and Mechanism of Selectivity of a New Protoporphyrinogen IX Oxidase Inhibiting Herbicide. Weed Sci. 59:290-298

Hammerton, J.L. 1967. Environmental Factors and Susceptibility to Herbicides. Weeds 15: 330-336

Hardman, L.L., E.S. Oplinger, E.E. Schulte, J.D. Doll and G. L. Worf. 1990. Field Bean. Alternative Field Crops Manual. University of Wisconsin – Extension. Madison, WI. [online] http://corn.agronomy.wisc.edu/Crops/FieldBean.aspx [accessed May 31, 2013]

Hartzler, B., C. Boerboom, G. Nice, P. Sikkema. 2006. Understanding glyphosate to increase performance. The Glyphosate, Weeds and Crop Series - Knowledge to Go: Purdue Extension 11 pages

Howe, C.M., M. Berrill, B.D. Pauli, C.C. Helbing, K. Werry, N. Veldhoen. 2004. Toxicity of Glyphosate-Based Pesticides to Four North American Frog Species. Env. Toxicol. Chem. 23:1928-1933

Hume, L., J. Martinez, K. Best. 1983. The Biology of Canadian Weeds . 60. *Polygonum convulvus.* Can. J. Plant Sci. 63: 959-971

Jordan, D.L., A.C. York, J.L. Griffin, P.A. Clay, P. R. Vidrine, D.B. Reynolds. 1997. Influence of application variables on efficacy of glyphosate. Weed Tech. 11:354-362

Jones, G.M., A. Vale. 2000. Mechanisms of Toxicity, clinical features, and management of diquat poisoning: a review. Clinical Tox. 38: 123-128

Kaplan, L. 1965. Archeology and Domestication in American Phaseolus (Beans). Econ. Bot. 19:358-368

Kaplan, L. 1981. What is the Origin of the Common Bean? Econ. Bot. 35:240-254

Kervégant, M.L. Merigot, M. Glaizal, C. Schmitt, L. Tichadou, L. deHaro. 2013. Paraquat Poisonings in France during the European Ban: Experience of the Poison Control Center in Marseille. J. Med. Tox. 9:144-147

King, D.L., A.W. Riddolls.1962 Damage to wheat and pea seed in threshing at varying moisture content. J. Agric. Eng. Res. 7:90-93. Cited in Bourgeois, L., J. Moes, E.H. Stobbe. 1996. Impact of threshing on hard red spring wheat seed vigour. Can. J. Pl. Sci. 76:215-221

Knezevic, S.Z., A. Datta, J. Scott, L.D. Charvat. 2009. Interactions between saflufenacil and glyphosate on selected weeds. [online] http://www.plantmanagementnetwork.org/pub/cm/research/2009/weeds/ [accessed July 2, 2013

Krausz, R.F., G. Kapusta, J.L. Matthews. 1996. Control of Annual Weeds with Glyphosate. Weed Tech. 10: 957-962

Kumaratilake, A.R., C. Preston. 2005. Low temperature reduces glufosinate activity and translocation in wild radish (*Raphanus raphanistrum*). Weed Sci. 53:10-16

Laing, D.R., P.G. Jones, J.H.C. Davis.1985. Common bean (*Phaseolus vulgaris* L.). In: ed. P.R. Goldsworthy and N.W. Fisher, The physiology of tropical grain legumes. Wiley, London. pages 305-351.

Lich, J.M., K.A. Renner, D. Penner. 1997. Interaction of glyphosate with post emergence soybean (*Glycine max*) herbicides. Weed Sci. 45:12-21

Lund, R.E. 1975. Tables for an approximate test for outliers in linear models. Technometrics, 17: 473-476.

Marini, R.P. 2003. Approaches to Analyzing Experiments of Treatments Plus Other Treatments. Hort. Sci. 38:117-120

Malik, V.S., C.J. Swanton, T.E. Micheals. 1993. Interaction of White Bean (*Phaseolus vulgaris* L.) Cultivars, Row Spacing, and Seeding Density with Annual Weeds. Weed Sci. 41: 62-68

McVicar, R. 2009. Dry Bean Narrow Row Production. Saskatchewan Agriculture. [Online] http://www.agriculture.gov.sk.ca/Default.aspx?DN=49ba6fc6-951a-4df1-9960-e3fe486dee3d [accessed March 1, 2010]

Mersey, B.G., J.C. Hall, D.M. Anderson, C.J. Swanton. 1990. Factors Affecting the Herbicidal Activity of Glufosinate-ammonium: Absorption, Translocation and Metabolism in Barley and Green Foxtail. Pest Biochem and Phys. 37:90-98

Miller, P.R, C.L. McDonald, D.A. Derksen, J. Waddington. 2000. The adaptation of seven broadleaf crops to the dry semiarid prairie. Can. J. Plant. Sci. 81:29-43

Miller, P. R., B.G. McConkey, G.W. Clayton, S.A. Brandt, J.A. Staricka, A.M. Johnston, G.P. Lafond, B.G. Schatz, D.D. Baltensperger, K.E. Neill. 2002. Pulse Crop Adaptation in the Northern Great Plains. Agron J. 94: 261-272

Muzik, T.J., W.G. Mauldin. 1964. Influence of environmental factors on the response of plants to herbicides. Weeds 12:142-145

Myers, R.L. 2002. Dry Edible Beans: A High Value Alternative Legume. The Jefferson Institute [online] http://www.jeffersoninstitute.org/pubs/dry_bean_guide.pdf [accessed March 1, 2010]

Ofitserova, M., R. Smith, M. Pickering. 2011. Glyphosate Analysis in Soy Beans, Corn and Sunflower Seeds by HPLC with Post-Column Derivatisation and Fluorescence Detection. The Application Notebook – Pickering Laboratories. Mountain View, CA.

Park S.J. 1985. Growing field beans in Canada. Agriculture Canada: Publication 1787/E. Harrow, Canada: Communications Branch, Agriculture Canada

Peterson, J., K. Hurle. 2001. Influence of climatic conditions and plant physiology on glufosinate-ammonium efficacy. Weed Res. 41: 31-39

Ratnayake, S., D.R. Shaw. 1992. Effects of Harvest Aid Herbicides on Soybean (*Glycine max)* Seed Yield and Quality. Weed Tech. 6:339-334

Reddy, K.N., K. Whiting. 2000. Weed Control and Economic Comparisons of Glyphosate-Resistant, Sulfonylurea-Tolerant and Conventional Soybean (*Glycine max)* Systems. Weed Tech. 14:204-211

Reigart, J.R., J.R. Roberts. 1999. Recognition and Management of Pesticide Poisonings, 5th edition. Washington, DC: United States Environmental Protection Agency. P 108-117

Retzlaff, R. 2004. Preharvest weed control vs. crop desiccation. Pulse Agronomy Network, Alberta Pulse Growers. Bulletin 14

Reithmuller, G., S. Loss, K.H.M. Siddique. 1999. Crop Updates – Pulse Crop Desiccation. [online] http://www.agric.wa.gov.au/PC_91437.html?s=0 [accessed September 5, 2013]

Riethmuller-Haage, I., L. Bastiaans, C. Kempenaar, V. Smutny, M.J. Kropff. 2007. Are pre-spraying growing conditions a major determinant of herbicide efficacy? Weed Res. 47:415-424

Ross, A.M., D.J. Childs. 1996. Herbicide Mode of Action Summary. Cooperative Extension. Purdue University and U.S. Department of Agriculture. [Online] http://www.extension.purdue.edu/extmedia/ws/ws-23-w.html

Royer, F., R. Dickinson. 1999. Weeds of Canada and the Northern United States. Edmonton, Alberta: The University of Alberta Press.

Sandberg, C.L., W.F. Meggit, D. Penner. 1980. Absorption, Translocation and Metabolism of ^{14}C-Glyphosate in Several Weed Species. Weed Res. 20:195-200

Saxton, A.M. 1998. A macro for converting mean separation output to letter groupings in Proc Mixed. In Proc. 23rd SAS Users Group Intl., SAS Institute, Cary, NC, pp 1243-1246.

Schneiter, A.A., B.J. Nagle. 1980. Effects of seeding rate and row spacing on dry bean production. Farm Res. 38: 8-11

Selleck, G.W., D.D. Baird. 1981.Antagonism with Glyphosate and Residual Combinations. Weed Sci. 29:185-190

Senseman, S.A. (ed) 2007. Herbicide Handbook 9th Edition. Weed Science Society of America. Lawrence, Kansas. 458 pages

Shahbazi, F., A. Saffar., M. Analooei. 2011. Mechanical damage to pinto bean seeds as affected by moisture content and impact velocity. Ag Eng Int. 13:1-11

Sharma, M.P. 1986. Recognizing Herbicide Action & Injury. Alberta Environmental Centre. Vegreville, Alberta. 138 pages

Shaw, D.R., J.C. Arnold. 2002. Weed Control from Herbicide Combinations with Glyphosate. Weed Tech. 16: 1-6

Sikkema, P.H., R.J. Vyn, C. Shropshire, N. Soltani. 2008.Integrated weed management in white bean production. Can. J. Plant Sci. 88:555-561

Skuterud, R., N. Bjugstad, A. Tyldum, K.S. Torresen. 1998. Effect of herbicides applied at different times of the day. Crop Prot. 17: 41-46

Soltani, N., C. Shropshire, P. Sikkema. 2009. Response of Corn to Preemergence and Postemergence Applications of Saflufenacil. Weed Tech. 23:331-334

Sprague, C. 2009. Preharvest Treatment Options for Dry Edible Beans [online] http://www.maes.msu.edu/ressta/saginawvalley/preharvest_drybeans_sprague.pdf [accessed February 16, 2010]

Sprague, C. 2012. Preharvest herbicide use in dry edible beans: Caution needs to be taken to avoid illegal residues [online] http://msue.anr.msu.edu/news/preharvest_herbicide_use_in_dry_edible_beans_caution_needs_to_be_taken_to_avoid_illegal_residues [accessed September 18, 2012]

Stahler, L.M. 1953. Contact Herbicides as Preharvest Defoliants or Desiccants. Journal of Agricultural and Food Chemistry. 2:183-187

Statistics Canada. 2009. Catalogue no 22-002-X, Field Crop Reporting Series, July 31 Estimate of Production of Principal Field Crops, Canada. August 2009, vol. 88, no. 5

Steckel, G.J., L.M. Wax, F.W. Simmons, W.H. Phillips II. 1997. Glufosinate effect on annual weeds is influenced by rate and growth stage. Weed Tech. 11: 484-488

Stewart, C.L., R.E. Nurse, A.S. Hamill, P.H. Sikkema. 2010 Environment and Soil Conditions Influence Pre- and Postemergent Herbicide Efficacy in Soybean. Weed Tech. 24:234-243

Teasdale, J.R., J.R. Frank. 1983. Effect of Row Spacing on Weed Competition with Snap Bean (*Phaseolus vulgaris*). Weed Sci. 31: 81-85

Thelen, K.D., E.P. Jackson, D. Penner. 1995. The basis for the hard-water antagonism of glyphosate activity. Weed Sci. 43:541-548

Vangessel, M.J., E.E. Schweizer, R.G. Wilson, L.J. Wiles, P. Westra. 1998. Impact of Timing and Frequency of In-Row Cultivation for Weed Control in Dry Bean (*Phaseolus vulgaris*). Weed Tech. 12: 548-553

Wagner, N., W. Reichenbecher, H. Teichmann, B. Tappeser, S. Lötters. 2013. Questions Concerning the Potential Impact of Glyphosate-Based Herbicides on Amphibians. Env. Toxicol. Chem. 32:1688-1700

Wang, C.J., Z.Q. Liu. 2007. Foliar Uptake of Pesticides – Present status and Future Challenge. Pest. Biochem and Phys. 87:1-8

Ware, G.W., D.M. Whitacre. 2004. Pesticide Book. Danvers: Meister Pub Co, Ohio. 488 pages.

Weaver, S.E., E.L. McWilliams. 1980. The Biology of Canadian Weeds . 44. *Amaranthus retroflexus.* Can. J. Plant Sci. 60: 1215-1234

Wilcoxson, R.D., B. Skovmand, A.H. Atif. 1975. Evaluation of wheat cultivars for ability to retard development of stem rust. Ann. App. Biol. 80: 275-281

Wilson, R.G., J.A Smith. 2002. Influence of Harvest Aid Herbicides on Dry Bean (*Phaseolus vulgaris*) Desiccation, Seed Yield and Quality. Weed Tech. 16:109-115

Yenish, J., P., F.L. Young. 2000. Effect of Preharvest Glyphosate Application on Seed and Seedling Quality of Spring Wheat (*Triticum aestivum).* Weed Tech. 14:212-217

Zagonal, J. 2011. Herbicide Application Timing in Preharvest Desiccation of Soybean Cultivars with Different Growth Habits. J. Env Sci. of Health 40:13-20