

**Halosulfuron: Crop Tolerance, Weed Control and Species Sensitivity in
Dry Beans**

By

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ABSTRACT

Halosulfuron: Crop Tolerance, Weed Control and Species Sensitivity in Dry Beans

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Twelve field experiments were conducted over a two-year period (2013, 2014) to evaluate the tolerance of white bean to halosulfuron and spectrum of weeds controlled with halosulfuron applied alone and in combination with trifluralin, pendimethalin, EPTC, dimethenamid-*P* or S-metolachlor applied preplant incorporated (PPI) and pendimethalin, dimethenamid-*P* or S-metolachlor applied preemergence (PRE). At 1 and 4 weeks after emergence (WAE), halosulfuron applied PPI or PRE, applied alone or in combination with trifluralin, pendimethalin, EPTC, dimethenamid-*P* or S-metolachlor caused $\leq 3\%$. At 4 and 8 WAE, halosulfuron applied PPI or PRE provided $\geq 90\%$ control of common lambsquarters, wild mustard, redroot pigweed and common ragweed and $\leq 60\%$ control of green foxtail. Weed biomass and density data reflected the weed control ratings. White bean yield with halosulfuron applied in combination with trifluralin, pendimethalin, EPTC, dimethenamid-*P* or S-metolachlor was equivalent to the weed-free control. Halosulfuron absorption, translocation and metabolism were studied in white and adzuki bean. Halosulfuron was absorbed more rapidly in adzuki bean than white bean. Adzuki

bean reached 90% absorption (t_{90}) 26.2 hours after treatment (HAT), while white bean required 40.1 HAT to reach t_{90} . The maximum halosulfuron absorption (A_{\max}) was higher in adzuki bean (75.7%) than in white bean (65.3%). More ^{14}C -halosulfuron was translocated to the apex, 1st trifoliolate, stem above the treated leaf and roots in adzuki bean than in white bean. The maximum radioactivity translocated out of treated leaf (T_{\max}) was higher in adzuki bean (17.7%) than in white bean (12.1%). Halosulfuron was broken down to the same metabolites in white and adzuki bean. The half-life of halosulfuron in adzuki bean and white bean was 16 HAT and ≤ 6 HAT, respectively. Differential tolerance of white and adzuki bean to halosulfuron can be attributed to greater absorption, greater translocation and decreased metabolism in adzuki bean.

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Chapter 1: General Introduction and Literature Review

1.1 Introduction of Dry Bean

1.1.1 Dry Bean History

The origin of dry bean production has not been located with certainty (Gentry 1969); but, common dry edible beans (*Phaseolus vulgaris* L.) were originally domesticated in Central and South America over 7000 years ago (Agricultural Marketing Resource Center (AgMRC 2011). Dry bean production moved northward through Mexico into United States. The first commercial dry bean industry was in New York state in the mid-1800s (AgMRC 2011). Approximately 0.7 to 0.8 million hectares of dry beans are produced annually in the US, with the largest number of hectares in North Dakota. As demand for grain legumes increased, the number of hectares planted to dry beans has increased in North America. In Canada, dry beans were first grown in Saskatchewan in the 1920s (Agriculture in the classroom 2010). Currently, Ontario is the leading dry bean producing province in Canada.

1.1.2 Dry Bean Production

Dry beans are an important field crop in Ontario. Black, cranberry, kidney and white beans are the primary market classes grown in the province. Some specialty market

classes of dry bean include adzuki, otebo, pinto and Small Red Mexican (SRM) beans which are primarily exported to Japan (Hensall District Co-operative (HDC) 2009). In 2010, 129,000 tonnes of dry bean were produced in Ontario on 54,000 hectares with a farm gate value of about \$90 million (McGee 2013). In Ontario, dry bean production decreased to 77,000 tonnes on 35,000 ha in 2011 and increased to 118,000 tonnes on 48,500 ha in 2012 (McGee 2013). Production of dry bean in Ontario fluctuates based on its profitability relative to other field crops.

1.1.3 Crop Rotation

The use of a diverse crop rotation results in increased dry bean yields. Determining an optimal crop rotation for dry beans depends on soil type, soil structure, stoniness, drainage, disease history, weed species composition, weed density and previous herbicide use (OMAFRA 2009). Weed problems can be decreased with the use of diverse crop rotations (Liebman and Dyck 1993). Planting dry beans after wheat (*Triticum aestivum* L.) can decrease soil compaction and dry bean root rot (*Fusarium Solani* f. sp. *phaseoli*) (Allmaras et al. 1988). A diverse crop rotation has been found to result in a decrease in weed seeds in the seedbank (Ball 1992). Also, a diverse but strategic rotation including cover crops will reduce soil erosion and increase nutrient retention in the field. For these reasons, most farmers rotate dry beans with corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.] and cereals in Ontario. A diverse crop rotation results in decreased weed and

disease incidence and increased dry bean yield.

1.1.4 Soil Structure and Tillage

Good soil structure and health are very important for dry bean production. Heavy clay textured soils have poor drainage, water logging and soil crusting and may result in reduced emergence and poor stands and therefore are not suitable for dry bean production (Robertson and Frazier 1978; Chen et al. 2005). Dry bean yield can be reduced 26% due to soil compaction and poor soil structure, which is more likely to occur on heavier soil types and seasons with excessive rainfall (Croissant et al. 1991). Soil compaction results in reduced dry bean yields due to reduced soil porosity, inhibited water movement and restricted root growth (Allmaras et al. 1988). Compaction is accentuated by heavy equipment traffic used for spraying, harvesting and transporting. Soil structure is one of many factors influences dry bean productivity.

Dry bean production is maximized when grown using conventional tillage. Tillage ensures that the soil is friable, loose and well-aerated which promotes optimal dry bean growth (Liebman et al. 1995). Proper tillage can reduce the risk of soil crusting, encourage uniform soil moisture, and facilitate good soil-to-seed contact all of which encourage the rapid, uniform emergence of dry beans (Robertson and Frazier 1978). Primary tillage in the fall followed by secondary tillage in the spring ensures the control of winter annual, biennial and simple perennial weeds but summer annual and creeping

perennial weeds are still a problem. One disadvantage of moldboard plowing in the fall is the burial of weed seeds deep into the soil profile where they can survive and persist contributing to weed problems far into the future (Fay and Olson 1978). Following tillage, rolling the soil to firm the seedbed helps ensure a more uniform seeding depth and better soil-to-seed contact which results in more uniform dry bean emergence and maturity at harvest time. Excessive tillage results in increased soil erosion which reduces dry bean growth and bean yield (Robertson and Frazier 1978). Conventional tillage is essential for optimal dry bean yields but care must be taken to avoid the negative consequences of excessive tillage. For some large-seeded dry beans, no-till production systems have been successful (Fageria et al. 2010). Dry beans produced under no-till production systems result in plants with short stature making it a good strategy for narrow row production. Both conventional and no-till production systems can be used successfully for dry bean production. Aleman (2001) reported a 10 and 15% yield increase with minimum tillage compared to no till and conventional tillage, respectively. Thus, optimal tillage methods should be chosen for individual farms.

1.1.5 Fertilizer

Proper nutrition contributes to profitable dry bean production. Nitrogen, phosphorus, potassium and zinc are the primary nutrients applied in dry bean production (Knodel et al. 2012). Normally, nitrogen fertilizers are not necessary for dry bean production, but, up to

100 kg ha⁻¹ nitrogen may result in increased dry bean yields especially on soils harbouring root rot. Soil tests are recommended to determine the amount of phosphorus and potassium needed in order to optimize yield potential. For example, 80 kg ha⁻¹ of phosphorus is needed when the sodium bicarbonate phosphorus soil test is only 0-3 ppm. Lack of phosphorus will result in slow growth and stunted plants (Fredeen et al. 1989). The application of fertilizer should meet the nutrient requirements of the crop. The most efficient way to use phosphorus is to place the fertilizer 2.5 to 5 cm to the side and 5 cm below the seed because dry bean seed can be damaged if high rates of fertilizers come in contact with the seed (OMAFRA 2009). Sometimes excessive fertilizer may result in greater weed densities and water contamination (Ongley 1996). The correct amount and type of fertilizer needs to be applied to maximize dry bean yield and profitability.

1.1.6 Insect Control

Insect damage can result in dry bean yield loss. Depending on the growth stage of dry beans, insect pests can be divided into five categories: seedling, foliage, flowers, pods and stored seeds (Abate and Ampofo 1996). Seedcorn maggot (*Delia platura* Meigen.), Mexican bean beetle (*Epilachna varivestis* Mulsant), potato leafhoppers (*Empoasca fabae* Harris) and bean leaf beetle (*Cerotoma trifurcata* Forster) are the primary dry bean insect pests in North America (Schoonhoven and Voysest 1991). All of these pests can affect dry bean yield. Seedcorn maggot damages dry beans shortly after germination

resulting in poor germination and emergence (Hein and Peairs 2006a); Mexican bean beetle feed on the underside of leaves, removing the epidermis resulting in "window-pane" damage (Hein and Peairs 2006b); potato leafhoppers curl and discolor leaves and may stunt dry bean growth, which is also known as "hopper burn" (Lindgren and Coyne 1995). Lack of adequate insect pest control can result in dry bean plant injury and decreased yield and quality.

1.1.7 Disease Control

Diseases can result in substantial dry bean yield losses in Ontario. The most common diseases in dry bean are root rots, common bean mosaic virus, white mold, anthracnose, soybean cyst nematode and bacterial blights (Hagedorn and Inglis 1986). Root rot in dry beans is caused by many pathogens, including species of *Pythium*, *Fusarium*, *Rhizoctonia*, and *Thielaviopsis* (Harveson et al. 2005). Root rot results in seed decay and damping-off resulting in watery and light brown lesions (Hagedorn and Inglis 1986). A number of different lesions on dry bean roots are caused by these different pathogens. Elongate, red to brown lesions are caused by *Fusarium solani*; shrunken, brown lesions and cankers are usually caused by *Rhizoctonia* spp.; while black root rot is always caused by *Thielaviopsis* (Hagedorn and Inglis 1986; University of Illinois 1999). *Sclerotinia sclerotiorum* is the causal organism for white mold in dry beans (Blad et al. 1978). At the beginning of white mold disease, above ground parts of dry bean plants are

attacked by white mold, with brown, soft lesions on flowering parts 10-15 cm above soil. Subsequently, nearby tissues are affected. Lesions may stay in the blossoms or move from blossoms to petioles, stems, leaves and other plant parts (Hagedorn and Inglis 1986). Anthracnose is another disease that can cause substantial yield losses and seed discoloration in dry bean. It is caused by the fungal pathogen *Colletotrichum lindemuthianum*, and is characterized by dark brown-black and slender lesions in leaf veins. Later, sunken symptoms can occur on both sides of the leaves (Markell et al. 2012). The use of certified dry bean seed may result in reduced incidence of common and halo blight, which may result in higher yield (Audy et al. 1996; Kolasinska et al. 2000). Without control of these pathogens, dry bean yields will be reduced.

1.1.8 Weed Control

Weed interference negatively affects dry bean yield and quality. Weeds are plants that grow in areas where they are not wanted and are unusually persistent (Radosevich et al. 2007). Weeds compete with dry beans for resources including moisture, nutrients and light resulting in yield losses. Pinto bean yield loss of 70% due to weed interference was reported by Blackshaw and Esau (1991). White bean yield losses of 58 to 81% due to weed interference was reported in studies by Malik et al. 1993, Chikoye et al. 1995, Soltani et al. 2014b, and Soltani et al. 2014c, respectively. In addition, weeds interfere with harvest efficiency and reduce dry bean quality due to seed staining (Chikoye et al.

1995). Some of the common weed species affecting dry bean production in Ontario include common lambsquarters (*Chenopodium album* L.), redroot pigweed (*Amaranthus retroflexus* L.), common ragweed (*Ambrosia artemisiifolia* L.), velvetleaf (*Abutilon theophrasti* Medic.), wild mustard (*Sinapis arvensis* L.), smartweed species (*Polygonum* spp.), common cocklebur (*Xanthium strumarium* L.), nightshade species (*Solanum* spp.), foxtail species (*Setaria* spp.), barnyard grass [*Echinochloa crus-galli* (L.) Beauv.], and crabgrass (*Digitaria* spp.) (Frick and Thomas 1992). The time of weed emergence relative to the growth stage of dry beans influences the extent of dry bean yield loss. The critical period of weed control is extremely important in dry bean production (Swanton and Weise 1991). Dawson (1964) reported that weeds which appeared in first 4 and 5 weeks of growing season resulted in significant yield loss in white bean. Woolley et al. (1993) reported that the critical period of weed control in dry beans was from second trifoliolate to the first flower stage from studies conducted in Ontario. Dry bean yields are closely correlated with weed management.

1.1.9 Desiccation

Desiccation is used in dry bean production to dry down both the crop and weeds prior to harvest. This practice improves dry bean quality and helps to ensure uniform crop maturity (Wilson and Smith 2002). Dry bean yields can be decreased by wind, hail and water damage during the desiccation period (Wilson and Smith 2002). Normally, seed

moisture of 16 to 20% is ideal for harvest. Low seed moisture at harvest may result in cracked seed coats and split seeds. High seed moisture at harvest may lead to staining from leaves, stems and dirt (Robertson and Frazier 1978; Long et al. 2010). The impact of seed moisture content at harvest is different for different types of dry beans. Large-seeded coloured beans will absorb more moisture than small-seeded beans after a rain. For example, cranberry bean is more susceptible to moisture retention than black bean (OMAFRA 2009). Desiccation is usually an integral part of overall dry bean production in Ontario.

1.1.10 Harvest

Dry bean phenological stage at harvest influences both yield and quality. Dry bean harvest should be completed when approximately 70% of the pods have turned brown (Smith 1986). Harvesting too early may lead to wrinkled seed coats while harvesting too late may result in greater harvest losses and split seed coats (Green et al. 2005; Junk 2005). Moisture is highly correlated with weather and dry beans are sensitive to weather during harvest. Seven to ten days of drying weather is required before harvesting beans after a significant rain event. Also, larger seeded beans require more time to dry down (OMAFRA 2009). Dry bean is either direct combined or pulled when 90% of pods have turned brown. If the beans are pulled, they are windrowed and harvested later (Robertson and Frazier 1978). Direct combining can decrease harvest losses, reduce split beans and

improve bean quality (Zyla et al. 2002). Adzuki, black, pinto and white bean with an upright growth habit are most suited for direct combining. Dry beans with an upright growth habit can be grown in narrow rows to increase yield and facilitate direct harvest (Welacky and Park 1987; Tinker and Michaels 1990). Proper harvesting time and method will maximize dry bean yield and quality.

1.1.11 Quality

Dry bean value is influenced by seed colour and quality. Consumers prefer to buy dry beans that are clean, bright and whole. Green weeds in the field at harvest time can stain beans which is undesirable. A harvest-aid herbicide can be applied before harvesting to kill weeds and also help to desiccate the crop (Wilson and Smith 2002). Quality is also maintained by storing different market classes of dry bean in separate bins (Robertson and Frazier 1978). Any glass, stones and other contaminants in beans results in reduced value. For beans that are intended for the export market, purity is a major concern. Even a single corn kernel appearing in a load of dry beans can be cause for rejection if the corn is genetically modified. All of the above factors must be considered because the value of dry beans is closely related to its quality.

1.2 Impact of weeds

Weed management is one of the most important aspects of successful dry bean production in Ontario. Weed interference can cause substantial yield losses in dry beans, especially when weeds emerge at the same time as the crop, due to competition for moisture, nutrients, and photosynthetically active radiation (Chikoye et al. 1996). In studies conducted in Ontario, weed interference in dry beans caused an average 58% yield loss (Peter Sikkema, personal communication). Bean yield loss due to weed interference was reported by several previous studies (Malik et al. 1993, Chikoye et al. 1995, Soltani et al. 2014b, and Soltani et al. 2014c). Weeds can affect not only yield, but also dry bean quality. Weeds present at harvest may cause seed staining and decrease harvesting efficiency (Wilson 1993). Thus, weed management is crucial for the production of high yields of high quality dry beans.

1.2.1 Grass Weed Control

There are five soil-applied herbicides registered for the control of annual grasses in dry beans in Ontario: trifluralin, pendimethalin, EPTC, dimethenamid-*P* and S-metolachlor. In addition there are five herbicides with grass activity that are applied postemergence (POST): quizalofop-p-ethyl, fenoxaprop-p-ethyl, sethoxydim, clethodim, and fluazifop-p-butyl (OMAFRA 2012).

Trifluralin and **Pendimethalin.** Trifluralin [α,α,α -trifluoro-2,6-dinitro-N,N-dipropyl-p-toluidine] and pendimethalin [N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine] are Group 3 herbicides that are microtubule polymerization inhibitors that provide control of annual grasses and some annual broadleaf weeds in dry beans (Zimdahl et al. 1984; OMAFRA 2012; Senseman 2007). Trifluralin must be applied preplant incorporated (PPI). Incorporation should be completed within 24 hours to reduce losses by photodegradation and volatilization (Spencer and Cliath 1974). Trifluralin and pendimethalin provide control of barnyard grass, smooth crabgrass [*Digitaria ischaemum* (Schreb) Muhl.], fall panicum (*Panicum dichotomiflorum* Michx.) and foxtail species. Also, common lambsquarters and redroot pigweed, are suppressed by these two herbicides (Betts and Morrison 1979; Ferrell et al. 2003; Soltani et al. 2013c). In Ontario, a limitation with trifluralin is that it is registered only on black, kidney and white beans while pendimethalin is registered on pinto, white, kidney, snap, lima, adzuki and white bean (PMRA 2014). Trifluralin and pendimethalin injury includes swollen root tips, hypocotyl swelling and cracking, stunted growth and delayed dry bean emergence (Glover and Schapaugh 2002). Trifluralin and pendimethalin may cause injury under cold, wet conditions. Injury occurs more frequently in light textured soils with low organic matter, since these herbicides are more biologically available in these soils (Morrison et al. 1989; Gunsolus and Curran 1999). Trifluralin and pendimethalin provide control of annual grass weeds in dry beans with a wide margin of crop safety.

EPTC. EPTC (S-ethyl N,N-dipropylthiocarbamate) is a Group 8 herbicide, which are cell growth disruptors and inhibitors that provide control of annual grass and some annual broadleaf weeds in dry beans (Senseman 2007). EPTC is highly volatile and should be incorporated immediately after application to reduce volatility losses (Gray 1965). It is registered on black, brown, cranberry, kidney, pinto, snap, yellow eye and white beans (PMRA 2008b), but not on adzuki bean in Ontario due to potential for crop injury. Most common annual grasses in Ontario are controlled by EPTC, including barnyard grass, crabgrass and foxtail species. EPTC also has some activity on lady's thumb (*Polygonum persicaria* L.), common lambsquarters, common chickweed (*Stellaria media* L.) and redroot pigweed (PMRA 2008b; Soltani et al. 2012d). Like the Group 3 herbicides, EPTC provides primarily annual grass control and in addition provides early season control of some annual broadleaf weeds.

Injury to dry beans from EPTC is influenced by dry bean market class, application rate, depth of incorporation and environment conditions. Injury symptoms, which include crinkled and malformed leaves, bud-seal, stunting and necrotic growing point, vary among market classes of dry bean (Urwin et al. 1996; Sikkema et al. 2006). Moisture stress, soil compaction, deep planting and damaged seeds all increase the potential for injury in dry beans (Wyse et al. 1976.) Injury from EPTC during dry weather can be reduced by delaying dry bean seeding 7 to 10 days after EPTC application (OMAFRA 2012). Dry bean injury following EPTC application is variable and is primarily

dependent upon market class and soil moisture.

Dimethenamid-*P* **and** **S-metolachlor.** Dimethenamid-*P*
[2-chloro-N-[(1-methyl-2-methoxy)ethyl]-N-(2,4-dimethyl-thien-3-yl)-acetamide] and
S-metolachlor

[2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl)acetamide] are two soil-applied Group 15 herbicides which are very long chain fatty acid synthesis inhibitors that provide control of annual grasses in dry beans (Trenkamp et al. 2004; Senseman 2007). Dimethenamid-*P* and S-metolachlor can be applied PPI or preemergence (PRE) in all market classes of dry beans except adzuki bean (Sikkema et al. 2008a; PMRA 2009). They cannot be used on muck, peat, or high organic matter soils. They provide control of specific annual grasses, including barnyard, crabgrass, foxtail species and witchgrass (*Panicum capillare* L.) (Sikkema et al. 2008a; Soltani et al. 2012d). They also provide control of nightshades and redroot pigweed (Soltani et al. 2012d; Hutchinson 2012). However, they are less effective on fall panicum, proso millet (*Panicum miliaceum* L.) and long-spine sandbur [*Cenchrus longispinus* (Hack.) Fern.] (Soltani et al. 2010a). Dimethenamid-*P* and S-metolachlor provide control of many annual grass and some annual broadleaf weeds in dry beans.

Dimethenamid-*P* and S-metolachlor may cause crop injury to dry beans depending on market class, soil type and environmental conditions. Crop injury symptoms include chlorosis followed by necrosis of the cotyledons, unifoliate and first trifoliate leaves

(Poling et al. 2009). In cases of severe injury the lower leaves may become completely necrotic and fall to the ground. Other injury symptoms include leaf distortion of the first trifoliolate and a delay in plant growth (Palmer et al. 2012). There is greater potential for injury when dimethenamid-*P* and S-metolachlor are applied PRE than PPI, and the small seeded market classes such as white and black beans are more susceptible than the large seeded market classes including kidney and cranberry beans (Soltani et al. 2007). In addition, there is greater injury on coarse-textured, low organic matter soils and in cold, wet weather conditions, since dry beans emerge slowly under these conditions and cannot metabolize the herbicide as rapidly. The potential for dry bean injury from the Group 15 herbicides is increased when applied to the small seeded market classes, during cool, wet conditions, and on coarse-textured, low organic matter soils.

POST Grass Herbicides. Quizalofop-p-ethyl [(R)-2-[4-[(6-chloro-2-quinoxalinyloxy]phenoxy]propanoic acid], fenoxaprop-p-ethyl [(±)-2-[4-[(6-chloro-2-benzoxazolyl)oxy]phenoxy]propanoic acid], sethoxydim [2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one], clethodim [(E,E)-(+)-2-[1-[[3-chloro-2-propenyl)oxy]imino]propyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one] and fluazifop-p-butyl [(R)-2-[4-[[5-(trifluoromethyl)-2-pyridinyl]oxy]phenoxy]propanoic acid] are Group 1 herbicides, which are Acetyl-Coenzyme A Carboxylase (ACCase) inhibitors, that are

applied POST for the control of annual and perennial grasses in dry beans (Senseman 2007). The annual grasses controlled by these herbicides include barnyard grass, crabgrass, fall panicum, foxtail species, proso millet and witchgrass. Quackgrass, a perennial grass, can also be controlled by some of these herbicides (Linscott and Vaughan 1990; Young and Hart 1997; McCullough et al. 2011; PMRA 2014). The above herbicides are registered on all market classes of dry beans with the exception that fenoxaprop-p-ethyl and clethodim are not registered on adzuki beans. These herbicides are applied POST when the annual grasses are in the two to five leaf stage (Soltani et al. 2006b; PMRA 2014). The efficacy of the above herbicides is reduced if rain falls within one hour after application, if the grasses are past the 5 leaf stage and if the correct adjuvant is not added (Bryson 1988). These herbicides do not have residual activity in the soil so grasses that emerge after application are not controlled (Scott et al. 1998; Baumann 2008).

Cost of Grass Herbicide in Dry Beans. There is a range in cost for the soil-applied grass herbicides in dry beans. Trifluralin has the lowest price of approximately \$20-40 ha⁻¹ depending on rate. The price of pendimethalin is around \$30 ha⁻¹. EPTC has the highest price among these herbicides, which is \$85-110 ha⁻¹. Dimethenamid-*P* and S-metolachlor are intermediate in price at \$45-64 ha⁻¹. In many situations, trifluralin is the product of choice since it provides effective control of annual grasses and some broadleaf weeds, has a wide margin of crop safety and has the lowest price. The POST

grass herbicides are similarly priced at around \$20 ha⁻¹ for annual grass control, but can cost as much as \$80 ha⁻¹ for the control of perennial grasses such as quackgrass. The herbicides registered in dry beans provide cost-effective control of annual grasses (Agris Co-op, Chatham, ON, 2013)

1.2.2 Broadleaf Weed Control

There are three herbicides with primarily broadleaf activity registered in dry beans in Ontario. Imazethapyr is the only soil-applied broadleaf herbicide (PMRA 2010). Bentazon and fomesafen are the only two POST broadleaf herbicides registered for use in dry beans in Ontario (Sikkema et al. 2004a; OMAFRA 2012). Dry bean growers in Ontario have limited options for broadleaf weed control.

Imazethapyr.

Imazethapyr

[2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-ethyl-3-pyridine carboxylic acid] is an imidazolinone herbicide that belongs to Group 2 herbicides or the acetolactate synthase inhibitors (ALS) inhibitors (Senseman 2007). Imazethapyr is absorbed by both roots and shoots of developing weed seedlings; therefore it can be applied PPI, PRE or POST (Bauer et al. 1995). In addition, imazethapyr provides season-long weed control due to its residual activity (Vencil et al. 1990). Imazethapyr may be used on all market classes of dry beans and it provides control of a range of

broadleaf weeds including wild buckwheat (*Polygonum convolvulus* L.), lady's thumb, common lambsquarters, mustard species, nightshade species, pigweed species and velvetleaf. However, there is widespread Group 2 resistant weeds in Ontario and imazethapyr will not control those biotypes (PMRA 2010). The efficacy of imazethapyr on common ragweed and common lambsquarters is inconsistent (Bauer et al. 1995; York et al. 1995). Annual grasses, including foxtail, barnyard grass, crabgrass and witchgrass, can also be controlled with imazethapyr.

There is potential for imazethapyr to injure dry beans (Wilson and Miller 1991; Arnold et al. 1993; Bauer et al. 1995; Blackshaw and Saindon 1996; Soltani et al. 2007). Injury occurs when the crop is stressed and cannot metabolize the herbicide as quickly. Despite the potential for injury, imazethapyr, the only soil-applied broadleaf herbicide registered for use on dry bean in Ontario, is an important component of an overall weed management strategy in dry bean production in Ontario.

Bentazon. Bentazon, 3-(1-methylethyl)-(1H)-2,1,3-benzothiadiazin-4(3H)-one 2,2-dioxide, is a selective benzothiadiazole POST herbicide, which is a Group 6 herbicide or photosynthesis inhibitors (Blackshaw et al. 2000; Senseman 2007). Bentazon provides control of lady's thumb, mustard species, velvetleaf, common cocklebur (*Xanthium strumarium* L.), nutsedge (*Cyperus* spp.), and common lambsquarters, (PMRA 2008a). Bentazon application timing is critical: weed control decreases as the size of the weeds at the time of application increases (Andersen et al. 1974), so if bentazon is sprayed too late,

some large weeds may escape. Also, bentazon has no residual activity, which means weeds that emerge after application will not be controlled (Smith and Hill 1990).

Bentazon injury is influenced by market class, adjuvant type, and environmental conditions. It is registered for use on all market classes of dry beans, except adzuki bean, due to the potential for severe injury in adzuki bean (Stewart et al. 2010). Bentazon can injure dry beans under hot, humid conditions and use of oil based adjuvants. The injury symptoms include yellowing, bronzing or burning of the leaves; however, injury usually is transient with no impact on yield (Renner and Powell 1992). Bentazon has some limitations as a herbicide for use in dry bean production, but is still a useful herbicide for the control of broadleaf weed escapes in dry beans.

Fomesafen. Fomesafen, 5-[2-chloro-4-(trifluoromethyl)phenoxy]-N-(methylsulfonyl)-2-nitrobenzamide, is a Group 14 diphenyl ether POST broadleaf herbicide or Protoporphyrinogen IX oxidase (PPO) inhibitors (Soltani et al. 2006a; Senseman 2007). It is registered for use all the market classes of dry beans, including adzuki beans. Fomesafen provides control of mustard species, pigweed species, common ragweed, lady's thumb, buckwheat and annual nightshades, but is weak on cocklebur, common lambsquarters and velvetleaf (Wilson 2005; Peachey et al. 2012). Fomesafen has similar limitations to bentazon, including limited spectrum of weeds controlled and a narrow window of application. Fomesafen provides short residual broadleaf weed control. Fomesafen can cause injury on dry bean; the injury symptoms

include speckling, bronzing, burning or crinkling of the leaves (Wilson 2005; Paul 2008). There is greater potential for dry bean injury if there are spray overlaps or if fomesafen is applied at above label rates (Soltani et al. 2006a). Fomesafen, another POST broadleaf herbicide, is an option for the control of emerged broadleaf weeds in dry beans.

Costs of Broadleaf Herbicides in Dry Beans. Imazethapyr, the only soil-applied herbicide in dry beans costs approximately \$40 ha⁻¹. There is not too much price difference between the two POST broadleaf herbicides. Bentazon is \$50-63 ha⁻¹, while fomesafen costs approximately \$50 ha⁻¹. The tankmix of bentazon plus fomesafen costs \$85 ha⁻¹. Farmers should choose their broadleaf herbicide based on the weed species present in each individual field rather than on herbicide price (Agris Co-op, Chatham, ON, 2013).

1.2.3 Tankmixes

Dimethenamid-*P*, S-metolachlor and trifluralin can be tankmixed with imazethapyr to increase the spectrum of weeds controlled (Soltani et al. 2003; Soltani et al. 2004a; Soltani et al. 2007; Soltani et al. 2010b). Soltani et al. (2007) reported that when imazethapyr is tankmixed with dimethenamid-*P* (1000 g ai ha⁻¹), the dose of imazethapyr required for the control of redroot pigweed, common lambsquarters, wild mustard, green foxtail [*Setaria viridis* (L.) P.Beauv.] and common ragweed was reduced. Compared to

imazethapyr (15 g ai ha⁻¹) applied alone, the level control of redroot pigweed, common lambsquarters and green foxtail was much higher when tankmixed with dimethenamid-*P*. Generally, the tankmix of *S*-metolachlor plus imazethapyr is safe for use in dry bean production, but serious injury may occur under some environmental conditions (Soltani et al. 2004a). When imazethapyr was tankmixed with trifluralin, the dose of imazethapyr required was reduced for 80 to 95% green foxtail, common lambsquarters and common ragweed control (Soltani et al. 2010b). The above tankmixes will control most of the common annual grass and broadleaf weeds found in dry bean production in Ontario.

Bentazon plus fomesafen is registered for the control of broadleaf weeds POST in Ontario. This tankmix provides control of common lambsquarters, wild buckwheat, annual nightshades, lady's thumb, wild mustard, pigweed species, common ragweed and velvetleaf; however, this tankmix is registered only for kidney and white beans (Wilson 2005). This tankmix caused more injury in black bean than cranberry bean, which matched the findings that small seeded black beans were more susceptible to soil-applied herbicides than larger seeded cranberry bean (Sikkema et al. 2004b). Moreover, higher doses of bentazon plus fomesafen resulted in more injury for black and cranberry beans than lower doses (Soltani et al. 2005). The tankmix of bentazon plus fomesafen provides broad spectrum broadleaf weed control in dry beans with the level of crop injury influenced by weather conditions and market class of dry beans.

There are tankmixes of a graminicide with a broadleaf herbicide for the control of both grass and broadleaf weeds POST in dry beans. Fenoxaprop-p-ethyl combined with

bentazon and fluazifop-p-butyl combined with fomesafen are two tankmixes registered for dry bean production in Ontario. Both of these tankmixes provide effective control of both grass and broadleaf weeds. However, fenoxaprop-p-ethyl combined with bentazon is registered only in kidney, pinto and white beans, while fluazifop-p-butyl plus bentazon is registered for all the market classes of dry beans (Wilson 2005; PMRA 2014). The combination of a POST graminicide with a POST broadleaf herbicide provides control of both grass and broadleaf weeds in dry beans.

1.2.4 Dry bean tolerance to Herbicides

Market Classes. The geographic origin of the various market classes of dry bean are different with corresponding differences in tolerance to herbicides (Hekmat et al. 2008). Dry bean is more susceptible to herbicides than soybean (*Glycine max* L. Merrill). With respect to weed management and herbicide tolerance, dry beans can be divided into three groups: 1) small seeded beans, such as white, otebo, pinto and black beans; 2) large seeded beans, such as kidney, brown, yellow and cranberry beans; and 3) adzuki beans. There is variable tolerance of dry bean market classes and cultivars to herbicides (Soltani et al. 2006a; Soltani et al. 2006b). Thus, market class specific weed management programs need to be developed.

Adzuki Bean. Adzuki beans are more susceptible to some herbicides than other market

classes of dry beans. EPTC (3300 g ai ha⁻¹) applied PPI reduced adzuki bean shoot dry weight 93%. Dimethenamid-*P* reduced adzuki bean yield 19 and 38% yields at the low and high rates, respectively. S-metolachlor at 3200 g ai ha⁻¹ decreased adzuki bean yield 19% and reduced shoot dry weight 46% (McClary et al. 1993; Soltani et al. 2005). Imazethapyr, the only soil-applied broadleaf herbicide for adzuki beans in Ontario, caused less than 6% injury and no yield loss at 75 and 150 g ai ha⁻¹ rates (Soltani et al. 2005). Trifluralin (2310 g ai ha⁻¹) applied PPI caused 9% injury, an 11% decrease in plant height and no decrease in yield loss of adzuki bean (Soltani et al. 2005). Trifluralin and imazethapyr are the only soil-applied herbicides with an adequate margin of crop safety in adzuki bean in Ontario.

Imazethapyr. Imazethapyr has a narrow margin of crop safety for some classes of dry beans (Wilson and Miller 1991; Arnold et al. 1993; Bauer et al. 1995; Blackshaw and Saindon 1996; Soltani et al. 2007). Dry bean injury symptoms from imazethapyr include crop stunting, yellow leaf margin, red to purple veins on lower side of the leaf, crinkled leaves and reduced yields (Wilson and Miller 1991). Pinto bean has excellent tolerance to imazethapyr at the 50 to 75 g ai ha⁻¹ rate (Arnold et al. 1993, Blackshaw and Esau 1991). In contrast, imazethapyr at 70 g ai ha⁻¹ caused 20% injury in white bean, although plants recovered and there was no decrease in yield (Renner and Powell 1992). Higher doses of imazethapyr, 70 and 100 g ai ha⁻¹, decreased dry bean height by 5 to 10 cm (Wilson and Miller 1991). Cold, wet conditions can increase bean injury from imazethapyr (BASF

2011). Differential tolerance to imazethapyr has been reported among years and cultivars within the pinto bean market class (Bauer et al. 1995). Imazethapyr rates need to be adjusted depending on market classes to minimize the potential injury to beans. Imazethapyr has a narrow margin of crop safety in dry beans with injury related to dose, market class and cultivar, and environmental conditions.

1.3 Halosulfuron-methyl

Halosulfuron-methyl (methyl 3-chloro-5-[[[(4, 6-dimethoxy-2-pyrimidinyl)amino] carbamoyl]amino]sulfonyl]-1-methyl-1*H*-pyrasole-4-carboxylate), belongs to sulfonylurea herbicide family (Group 2) (Senseman 2007). There are three Group 2 herbicide families registered for use in Ontario; sulfonylureas, imidazolinones, and triazolopyrimidines. Group 2 herbicides inhibit acetolactate synthase (ALS), an enzyme involved in the biosynthesis of branched chain amino acids (Brown 1990) including valine, leucine, and isoleucine (Duggleby et al. 2008). Halosulfuron can be taken up by both roots and foliage, inhibiting growth of susceptible plants (Soltani et al. 2009). The Group 2 herbicides have been an integral component of weed management in numerous crops for many decades in Canada. Group 2 herbicides have a wide range of crop selectivity, are low use rate herbicides, have high efficacy and low mammalian toxicity (Senseman 2007). Globally, there are more than 50 active ingredients that are ALS inhibitors (Boutsalis 2001). Halosulfuron provides control of many broadleaf weeds

including redroot pigweed, velvetleaf, wild mustard and yellow nutsedge (*Cyperus esculentus* L.). Weed injury symptoms usually appear within 5 to 7 days, including chlorosis and necrosis of the growing point, cessation of plant growth, and reddening of the veins of the lower leaf surface (Senseman 2007). Halosulfuron is a Group 2 herbicide that inhibits ALS and provides control of broadleaf weeds in a number of crops.

Halosulfuron has a proposed use rate of 35 to 70 g ai ha⁻¹ in dry bean in Ontario (Soltani et al. 2009). It has a much lower use rate than some other herbicides, such as pendimethalin and S-metolachlor where use rates are 1080 and 1050-1600 g ai ha⁻¹, respectively (Senseman 2007). Unlike some of the early sulfonylurea herbicides such as chlorsulfuron and metsulfuron which have long persistence in the soil, halosulfuron has a half-life in the soil of 1 to 27 days (Amrhein and Gerber 1985; Baber and Marmor 2002; Senseman 2007). In contrast to some other sulfonylurea herbicides such as foramsulfuron and nicosulfuron which provide limited residual weed control, halosulfuron provides full season residual broadleaf weed control. Halosulfuron soil adsorption is correlated with soil organic carbon content and inversely related to soil pH (Dermiyati and Yamamoto 1997a). Increasing temperature, high organic matter and lower soil pH resulted in more rapid degradation of halosulfuron with degradation in the soil varying with soil moisture levels and soil type (Dermiyati and Yamamoto 1997b). The sorption of halosulfuron to soil was highly correlated with soil organic matter and soil pH (Dermiyati and Yamamoto 1997b). Halosulfuron is degraded by microbial degradation and through chemical hydrolysis (Grey et al. 2007). The herbicide will hydrolyze more rapidly when soil pH is

less than 4.5. The lower rate of halosulfuron (35 g ai ha⁻¹) is recommended on lighter textured with low organic matter soils (Senseman 2007). Halosulfuron is a low dose herbicide that provides residual control of broadleaf weeds.

1.3.1 Halosulfuron Weed Control

Halosulfuron applied POST provides control of some broadleaf and sedge weeds. Halosulfuron provides control of many broadleaf weeds including velvetleaf, lady's thumb, common cocklebur, wild mustard and yellow nutsedge (Senseman 2007). When halosulfuron was applied POST at 70 g ai ha⁻¹, there was no growth of yellow nutsedge at 26 days after application (Ferrell et al. 2004). Similar results were reported by Earl et al. (2004) who found that halosulfuron applied POST at 63 g ai ha⁻¹ killed yellow nutsedge rhizomes and there was no regrowth. In addition, Nelson and Renner (2002) reported 97% control of yellow nutsedge with halosulfuron applied POST at 35 g ai ha⁻¹; and Vencil et al. (1995) reported 95% control of yellow and purple nutsedge with 53 g ai ha⁻¹ halosulfuron applied PRE, POST, or PRE followed by POST. Halosulfuron applied POST (35 to 70 g ai ha⁻¹) was ineffective on common lambsquarters (Hart and Maxwell 1995; Isaacs et al. 2003). Halosulfuron applied POST provides control of some broadleaf and sedge weeds.

Halosulfuron applied prior to weed emergence provides good control of some broadleaf weeds. Brown and Masiunas (2002) reported that halosulfuron (110 g ai ha⁻¹)

applied preemergence (PRE) provided more than 88% of redroot pigweed, velvetleaf and common lambsquarters in pumpkins. Since halosulfuron does not control grasses (Buker et al. 1998) it can be combined with a grass herbicide for broad spectrum weed control (Bicksler and Masiunas 2005). Soil-applied applications of halosulfuron provide effective control of some broadleaf weeds but requires the addition of a grass herbicide for broad spectrum weed control.

1.3.2 Dry Bean Tolerance to Halosulfuron

Herbicide tolerance in dry beans is market class and active ingredient specific. For example, thifensulfuron plus bentazon applied POST caused 50% injury to navy bean (Wall 1995); imazethapyr (70 g ai ha⁻¹) did not cause any injury in pinto bean, but caused 20% injury in white bean (Blackshaw and Esau 1991; Renner and Powell 1992; Arnold et al. 1993); pyroxasulfone applied PPI caused 80% injury to pinto and SRM beans (Soltani et al. 2008b); and bentazon caused over 60% injury in adzuki bean, but is safe for use on black, kidney and white beans (Stewart et al. 2010; OMAFRA 2012). Therefore, choosing the correct herbicide for each market class of dry beans is important, otherwise, economic loss may result.

Halosulfuron is safe for use on most of the dry bean market classes grown in Ontario with the exception of adzuki, mung, and snap bean. Soltani et al. (2009) evaluated the crop safety of halosulfuron applied at 35 and 70 g ai ha⁻¹ PPI, PRE, and POST to black,

cranberry, kidney, otebo, pink, pinto, small red Mexican (SRM), and white beans in Harrow, Ridgetown, and Exeter, Ontario. They found that halosulfuron applied PPI, PRE, and POST caused 1%, 2%, and 5% crop injury, respectively. The injury symptoms caused by halosulfuron included chlorosis, necrosis, stunting, and death of the growing point (Soltani et al. 2009). In contrast, there is not an adequate margin of crop safety for adzuki beans to halosulfuron when applied POST (Stewart et al. 2010). Stewart et al. (2010) evaluated the crop safety of halosulfuron at 35 and 70 g ai ha⁻¹ applied POST to eight different market classes of dry bean in Ridgetown and Exeter, Ontario. Halosulfuron (70 g ai ha⁻¹) applied POST caused up to 70% injury in adzuki bean and decreased height up to 70%. Stewart et al. (2010) reported that halosulfuron at 35 and 70 g ai ha⁻¹ applied POST caused 67 and 86% injury in adzuki beans, respectively. Soltani et al. (2009) reported that halosulfuron caused 10 and 5% injury to black, cranberry, kidney, otebo, pinto, SRM and white beans 1 and 2 weeks after application, respectively, however, the injury was transient with no injury symptoms observed 4 weeks after application. Halosulfuron applied POST did not reduce dry bean height in the above study. Halosulfuron applied POST at 35 and 70 g ai ha⁻¹ reduced adzuki bean yield 58 and 68%, respectively (Soltani et al. 2009). Soltani et al. (2012b) found halosulfuron-methyl and bentazon mixtures caused early injury in black, white, cranberry and kidney bean, but plants recovered with no reduction in final plant height, shoot dry weight, seed moisture content and yield. The addition of bentazon to halosulfuron did not result in greater crop injury (Soltani et al. 2012b). Silvey et al. (2006) evaluated the effect of halosulfuron

applied PRE, POST, and PRE follow by POST on snap bean in 1996 and 1997 in Clinton, North Carolina on an Orangeburg loamy sand soil with less than 2% organic matter and a pH of 5.6. They found halosulfuron applied PRE, POST, PRE fb POST resulted in 4%, 8%, and 5% injury, respectively. Although visible crop injury was less than 10% in this study, halosulfuron applied at 35, 53 and 70 g ai ha⁻¹ reduced snap bean yield 11, 7, and 15%, respectively. Soltani et al. (2013a) reported that halosulfuron applied POST at 35 and 70 g ai ha⁻¹ caused 50 and 75% injury in mung bean injury 2 weeks after application, respectively. Halosulfuron has a wider margin of crop safety applied PPI or PRE than POST and causes greater injury in adzuki, mung and snap bean.

1.3.3 Halosulfuron Weed Management (PPI and PRE)

Halosulfuron applied PPI or PRE provides annual broadleaf weed and sedge control. Grichar et al. (2003) reported 92% purple nutsedge control with halosulfuron applied PRE at 66 g ha⁻¹. In contrast, Webster (2006) found that halosulfuron applied PRE was less effective for the control of yellow nutsedge than when applied POST. Halosulfuron is more efficacious on annual broadleaf weeds when applied PPI or PRE than POST. Brown and Masiunas (2002) reported that halosulfuron applied PRE provided 94, 88 and 90% control of redroot pigweed, velvetleaf and common lambsquarters 21 days after treatment (DAT) and 98%, 96% and 98% control of these weeds 45 DAT, respectively. Halosulfuron applied PRE at 27 g ai ha⁻¹ provided control of morningglory species in

cucumber production (Trader et al. 2007). Trader et al. (2007) reported 88% control of common ragweed and 67% to 98% control of smooth pigweed with halosulfuron applied in combination with clomazone plus ethalfluralin in cucumber and pumpkin. Halosulfuron applied PPI and PRE provides control of many annual broadleaf weeds and sedges.

1.3.4 Halosulfuron Weed Management (POST)

Halosulfuron provides broadleaf weed and sedge control applied POST. Halosulfuron applied POST provided excellent control of redroot pigweed, common ragweed and wild mustard but poor control of common lambsquarters (38%) in a study conducted by Soltani et al. (2013d). Halosulfuron applied POST at 35 g ai ha⁻¹ provided poor control of hairy nightshade (55%) and large crabgrass [*Digitaria sanguinalis* (L.) Scop.] (58%) in potato trials conducted in 2004 and 2005 in south-central Washington on a Quincy sand soil (Boydston 2007). The addition of EPTC (2000 g ai ha⁻¹) to halosulfuron improved early-season hairy nightshade control, but poor weed control was found by row closure time. Bentazon is a Group 6 photosynthesis inhibitor that belongs to the benzothiadiazoles herbicide family (Retzinger and Mallory-Smith 1997). It has a different mode of action compared to halosulfuron. Bentazon can control broadleaf weeds including purslane (*Portulaca oleracea* L.), wild radish (*Raphanus raphanistrum* L.), hairy galinsoga [*Galinsoga ciliata* (Raf.) Blake], common groundsel

(*Senecio vulgaris* L.), jimsonweed (*Datura stramonium* L.), velvetleaf, lady's thumb, wild mustard, common cocklebur, shepherd's purse [*Capsella bursa-pastoris* (L.) Medik.], and common chickweed [*Stellaria media* (L.) Vill.] (Senseman 2007; Soltani et al. 2013d). In many cases, halosulfuron should be combined with other herbicides for broad spectrum broadleaf weed control when applied POST. Grichar et al. (2003) reported 77% to 95% purple nutsedge control with halosulfuron applied POST at 66 g ha⁻¹. Nelson and Renner (2002) observed 97% control of yellow nutsedge with halosulfuron applied POST at 35 g ai ha⁻¹. Halosulfuron applied POST provides poor control of grass weeds. Buckelew (2005) reported that halosulfuron has no effect on large crabgrass, goosegrass and fall panicum. Halosulfuron applied POST provides excellent control of yellow and purple nutsedge and some annual broadleaf weed species.

Since halosulfuron is less effective in terms of grass weed control, it requires a grass herbicide tankmix partner (Buker et al. 1998). There are five soil-applied grass herbicides registered in dry beans in Ontario: trifluralin, pendimethalin, EPTC, dimethenamid-*P* and S-metolachlor (OMAFRA 2012). All of them provide effective control of annual grass weeds including green foxtail, large crabgrass and barnyard grass (Senseman 2007; OMAFRA 2012). Powles et al. (1997) wrote that the repeated use of a single herbicide contributes to the evolution of herbicide resistant weed biotypes. Herbicide rotation and herbicide tankmixes may delay the evolution of resistant weeds, so the inclusion of multiple herbicide modes of action is more sustainable. The effect of a single herbicide compared to a herbicide tankmix on the evolution of resistant weeds is illustrated in

Figure 1.1. All five of the grass herbicides registered for use in dry bean in Ontario have a different mode of action than halosulfuron (Senseman 2007), which is beneficial because the use of multiple modes of action can delay the selection of herbicide resistant weeds providing that they have overlapping activity on each weed species.

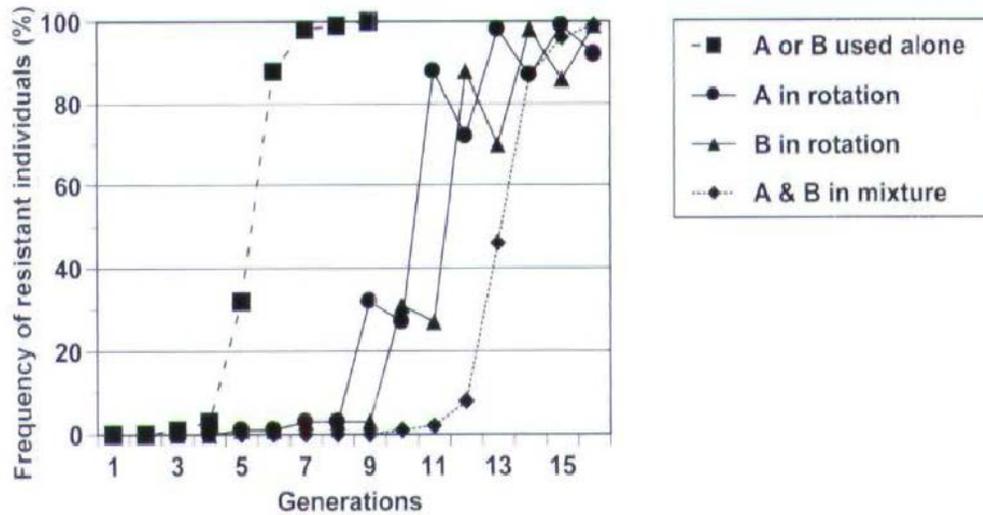


Figure 1.1. Predicted increase of herbicide resistant individuals over time [Source: Powles et al. 1997].

1.3.5 Use of Radioactive Labeling for Herbicide Metabolism

Pesticides, including herbicides, insecticides, fungicides, nematicides, and rodenticides are an important component in global crop production (Ongley 1996). Pan-Uk (2003) reported that there are several hundred pesticides used, with a volume of 3 billion kg and a value of \$40 billion annually. However, high toxicity and highly persistent herbicides can damage the environment and human health (Withgott and Brennan 2008). It is important to understand the metabolic degradation, mechanism of

action and environmental behavior of herbicides, so that they can be used in a sustainable fashion. Radioactive labeled herbicides allow for the determination of the absorption, translocation and degradation of herbicides in plants. In order for herbicides to be effective, they must be absorbed by the plant and moved to the site-of-action (Crafts 1962).

Phaseolus and *Vigna* are the two main dry bean genus in Ontario. Adzuki bean (*Vigna angularis*) is an important crop in Asia. It is sixth-largest crop in Japan (Sacks 1977). Stewart et al. (2010) reported that halosulfuron applied POST can cause 70% injury in adzuki bean. In addition, mung bean (*Vigna radiata*) has been reported to be susceptible to halosulfuron applied POST (Soltani et al. 2013a). In contrast, Soltani et al. (2009) reported halosulfuron applied POST caused less than 10% injury to black, cranberry kidney, otebo, pinto, small red Mexican and white bean which are all *Phaseolus vulgaris*. *Vigna angularis* and *Vigna radiata* are more susceptible to halosulfuron applied POST than *Phaseolus vulgaris*. The cause of increased halosulfuron injury in adzuki bean is unknown. Studies using radioactive labeled halosulfuron can be useful to document the differences in absorption, translocation and metabolism of ¹⁴C-halosulfuron between two dry bean genus.

The physiological selectivity of ALS herbicides is due, in part, to differential absorption, translocation, and metabolism (Dubelman et al. 1997; Ma et al. 1997; Gallaher et al. 1999). Corn and wheat metabolize halosulfuron more rapidly than soybean (Dubelman et al. 1997). ¹⁴C-halosulfuron was quickly degraded by corn and wheat while

it was degraded very slowly by soybean. In soybean, 96 to 86% of halosulfuron radioactivity was unchanged after 6 to 168 hours, respectively, while almost 100% halosulfuron radioactivity was changed by corn and wheat after 6 hours (Dubelman et al. 1997). Different halosulfuron absorption and translocation influenced herbicide efficacy of weeds. Sicklepod is more tolerant to prosulfuron than common cocklebur and common lambsquarters. More rapid metabolism and less translocation of prosulfuron was shown in sicklepod than common cocklebur and common lambsquarters (Ma et al. 1997). Primisulfuron was absorbed less and translocated less than nicosulfuron in broadleaf signalgrass, which is the reason that broadleaf signalgrass is susceptible to nicosulfuron and tolerant to primisulfuron (Gallaher et al. 1999). Nicosulfuron was absorbed 20% more than primisulfuron in broadleaf signalgrass at 72 HAT. Also, less than 4% of primisulfuron translocated out of the treated leaf, but up to 15% of nicosulfuron was translocated from the treated leaf.

1.4 Research Hypothesis and Objectives

The hypotheses for this research were: 1) halosulfuron plus a soil-applied grass herbicide applied PPI or PRE will provide broad spectrum weed control in white beans; and 2) the increased sensitivity of adzuki bean relative to white bean to halosulfuron applied POST is due to reduced metabolism.

The objectives of the experiments were: 1) to determine the degree of crop injury,

level of weed control, and dry bean yield when halosulfuron is used as a tankmix with a soil-applied grass herbicides applied either PPI or PRE; and 2) to evaluate the level of absorption, translocation, and metabolism of ^{14}C -halosulfuron in white and adzuki beans.

Chapter 2: Evaluation of halosulfuron tankmixes applied PPI in white bean

This chapter is a modified version of the following manuscript published in Canadian Journal of Plant Science.

Li, Z., R. Van Acker, D. E. Robinson, N. Soltani, and P. H. Sikkema. 2016. Halosulfuron tankmixes applied preplant incorporated for weed control in white bean (*Phaseolus vulgaris* L.). Canadian Journal of Plant Science. 96:81-88.

2.1 Abstract

Six field experiments were conducted over a two-year period (2013 and 2014) to evaluate the tolerance of white bean and spectrum of weeds controlled with halosulfuron applied preplant incorporated (PPI) alone or tankmixed with trifluralin, pendimethalin, EPTC, dimethenamid-*P* or S-metolachlor. Halosulfuron applied alone or in tankmix with trifluralin, pendimethalin, EPTC, dimethenamid-*P* or S-metolachlor caused $\leq 2\%$ injury 1 and 4 weeks after emergence (WAE). Halosulfuron applied PPI controlled common lambsquarters, wild mustard, redroot pigweed and common ragweed greater than 90% and green foxtail less than 60% at 4 and 8 WAE. Weed biomass and density followed a similar pattern. White bean yield with halosulfuron applied alone or in tankmix with a soil-applied grass herbicide was equivalent to the weed-free control.

2.2 Introduction

Ontario is the largest white bean (*Phaseolus vulgaris* L.) producing province in Canada. In 2014, white bean was grown on approximately 36,400 ha in Canada of which 24,300 ha, or 67%, was in the province of Ontario (Statistics Canada 2015). In 2014, there was 77,700 tonnes of white bean produced in Canada of which 59,600 tonnes, or 77%, was produced in Ontario with a farm gate value of over \$38 million (Kumuduni 2014; Statistics Canada 2015).

Weed management is a critical component of successful white bean production, since white bean is very susceptible to weed interference. Weeds compete with white bean for resources and can decrease white bean quality and yield (Wilson et al. 1980; Blackshaw and Esau 1991; Chikoye et al. 1995; Chikoye et al. 1996). In a study by Chikoye et al. (1995) in Ontario, Canada, white bean yield was reduced 58% due to weed interference. Malik et al. (1993) reported yield losses of 77% in white bean due to weed interference. More studies showed white bean yield losses of 81% and 68% due to uncontrolled weeds (Soltani et al. 2014a; Soltani et al. 2014b). Weeds also can decrease harvest efficiency or cause seed staining, which results in reduced bean quality (Wilson et al. 1980; Wilson 1993) and dockage at the point of sale.

Halosulfuron, a sulfonylurea herbicide, applied preplant incorporated (PPI) controls many annual broadleaf weeds that are commonly found in Ontario including, common lambsquarters, redroot pigweed, velvetleaf, wild mustard, common cocklebur (*Xanthium pennsylvanicum* L.), jimsonweed and lady's thumb. It also has activity on nutsedge

species (*Cyperus spp.*) (Senseman 2007). Halosulfuron was first registered for weed control in dry beans in Ontario in 2014. It can be applied preplant incorporated (PPI), preemergence (PRE) or postemergence (POST) in white bean (Soltani 2009). There is a wider margin of crop safety in white bean when halosulfuron is applied PPI or PRE compared to POST (Soltani 2009). Halosulfuron is more efficacious on annual broadleaf weeds when applied PPI or PRE than POST. In a study by Brown and Masiunas (2002), halosulfuron applied PRE provided 94, 88 and 90% control of redroot pigweed, velvetleaf and common lambsquarters 3 weeks after application (WAA), respectively. At 6 WAA, the control of the above three weeds increased to 98, 96 and 98%, respectively. Halosulfuron, applied POST, controlled lambsquarters only 38% in a study conducted by Soltani et al. (2013c). Halosulfuron suppresses annual grasses with only 50% control of green foxtail (Senseman 2007; Soltani et al. 2014b).

Halosulfuron tankmixed with an effective soil-applied grass herbicide may expand the spectrum of weeds controlled. There are five soil-applied herbicides registered for control of annual grasses in white bean in Ontario: trifluralin, pendimethalin, EPTC, dimethenamid-*P* and S-metolachlor. These herbicides control some annual grass species including green foxtail, giant foxtail (*Setaria faberii* Herrm.), yellow foxtail [*Setaria lutescens* (Weigel) Hubb.], large crabgrass, smooth crabgrass [*Digitaria ischaemum* (Schreb.) Muhl.], barnyard grass, witchgrass (*Panicum capillare* L.) and fall panicum (Senseman 2007; OMAFRA 2012). Soltani et al. (2012d) reported that trifluralin, EPTC, dimethenamid-*P* and S-metolachlor provided 95% control of green foxtail.

The objective of this research was to determine the weed emergence pattern, the spectrum of weeds controlled, the level of crop injury and white bean yield when halosulfuron is applied alone or in combination with trifluralin, pendimethalin, EPTC, dimethenamid-*P* or S-metolachlor applied PPI.

2.3 Materials and Methods

Six field experiments were conducted over a two-year period (2013 and 2014) at the Huron Research Station near Exeter, Ontario (2013 and 2014) and at the University of Guelph Ridgetown Campus near Ridgetown, Ontario (2014). The soils for the two trials near Exeter in 2013 were a Brookston clay loam with 29% sand, 44% silt, 27% clay, 3.6% organic matter and pH of 7.7 at site 1; and 18% sand, 46% silt, 36% clay, 4.7% organic matter and pH of 7.5 at site 2. The soils for the two trials near Exeter in 2014 were 31% sand, 42% silt, 27% clay, 3.8% organic matter and pH of 7.7 at site 3; and 41% sand, 40% silt, 19% clay, 3.3% organic matter and pH of 7.7 at site 4. The soils for the two trials near Ridgetown in 2014 were a Fox sandy loam with 50% sand, 25% silt, 25% clay, 2.9 % organic matter and pH of 7.1 for sites 5 and 6. Seedbed preparation consisted of fall moldboard plowing followed by two passes with a field cultivator with rolling basket harrows in the spring.

The experimental design was a randomized complete block with four replications. Treatments are listed in Table 2.1. Each plot was 3 m wide consisting of four rows

(spaced 0.75 m apart) of 'T9905' white bean (Thompsons Limited, Hensall, ON). Plots were 10 m long at Exeter and 8 m long at Ridgetown. White bean was seeded at a rate of 250,000 seeds ha⁻¹ in late May to early June of each year. Beans were planted on May 27th and June 7th, 2013 for site 1 and 2 in Exeter, respectively. In 2014, beans were planted on June 4th, 10th, 6th, and 18th for site 3 to 6 in Exeter and Ridgetown, respectively.

The herbicides were applied on the same day before seeding and were immediately incorporated into the soil to a depth of 5 cm with two passes (in opposite directions) of an S-tine cultivator with rolling basket harrows. Herbicides were applied with a CO₂ pressurized backpack sprayer calibrated to deliver 200 L ha⁻¹ of spray solution at a pressure of 200 kPa using ULD 120-02 (Hypro, New Brighton, MN) ultra low drift nozzles. The spray boom was 1.5 m in length with four nozzles spaced 50 cm apart.

White bean injury and weed control were estimated visually on a scale of 0 (no injury/control) to 100% (complete plant death) 1 and 4 weeks after emergence (WAE), and 4 and 8 WAE, respectively. Weed density and dry weight were determined 8 WAE by counting and cutting the weeds at the soil surface in two 0.5 m² quadrats per plot and separating by species. Quadrats were placed between the two middle rows of white bean in each plot a minimum of 1 m inward from the front and back of the plot. Plants were dried at 60 C in an oven to a constant weight and then weighed. White bean was considered mature when 90% of the pods in the weed-free control had turned from green to golden in colour. White bean was harvested from the center two rows of each plot with

a plot combine. White bean weight and moisture content were recorded and yields were adjusted to 18% seed moisture content.

Data were analyzed using PROC MIXED in SAS 9.3 (SAS Institute Inc., Cary, NC). Herbicide treatment was considered a fixed effect, while location, block within location, and their interactions were considered random effects. Significance of fixed effects were tested using F-tests and random effects were tested using a Z-test of the variance estimate. The UNIVARIATE procedure was used to test data for normality and homogeneity of variance. Any treatment assigned a value of zero was excluded from the analysis: weedy and weed free control for injury; weed free control for weed control and weed density and weed dry weight. All analyses were considered significant at $\alpha=0.05$. Tukey adjusted means comparison was conducted to determine significant differences among the treatments evaluated.

Weed emergence data was collected weekly from 1 to 10 WAE from two 0.25 m² permanent quadrats in the weedy control and halosulfuron treatment. The data from the two quadrats were analyzed by PROC MIXED to determine differences and then combined for analysis. The percent of accumulated weed emergence in weedy control and halosulfuron treatment were based on the accumulated number of weeds in weedy control and halosulfuron treatment. Also, average percent of weeds where halosulfuron was applied based on the accumulated number of weeds in the weedy control is presented in Figure 2.1, which was shown as y_3 . Then, weed emergence curves were obtained by nonlinear regression using the sigmoidal equation:

$$[1] \quad y = a(1 - e^{-bx})^c$$

where y represents the percent of total accumulated weed emergence at weeks after white bean emergence x , e is the base of the natural logarithm, and a , b and c are the parameters. The curves were plotted in SigmaPlot v. 12.1 (Systat Software Inc., Chicago, USA). The difference in weed emergence in the weedy control compared to the halosulfuron treated plot was analyzed by two sample t-test in SAS 9.3 (SAS Institute Inc., Cary, NC). The mean comparison of two treatments was also tested.

2.4 Results and Discussion

2.4.1 Crop Injury

Data were pooled across environments. Trifluralin, pendimethalin, EPTC, dimethenamid-*P*, S-metolachlor, halosulfuron, trifluralin + halosulfuron, pendimethalin + halosulfuron, EPTC + halosulfuron and S-metolachlor + halosulfuron, applied PPI, injured white bean $\leq 2\%$. Dimethenamid-*P* + halosulfuron caused 2% injury at 1 and 4 WAE (Table 2.1). Soltani et al. (2014) reported no injury in white bean with trifluralin, S-metolachlor or halosulfuron applied PPI while S-metolachlor + halosulfuron resulted in 1% injury to white bean. Halosulfuron, applied POST, caused 9, 4 and 1% injury in white bean at 1, 2 and 4 weeks after application (WAA), respectively (Soltani et al. 2012a). In the same study (Soltani et al. 2012a) conclusively showed that it is safer to apply halosulfuron PPI or PRE than POST in white bean. These results support adequate crop

safety in white bean with the soil-applied grass herbicides tankmixed with halosulfuron applied PPI. These results are consistent with Soltani et al. (2014) who reported that halosulfuron, trifluralin + halosulfuron, and S-metolachlor + halosulfuron did not damage white bean. In previous studies, it has been reported that halosulfuron, applied PPI, is safe for use on most market classes of dry beans with the exception of mung and snap bean (Silvey et al. 2006; Soltani et al. 2009; Stewart et al. 2010; Soltani et al. 2013a). Halosulfuron, applied POST, caused 58 to 70% injury in adzuki bean and reduced adzuki bean height 52 to 70% (Stewart et al. 2010; Soltani et al. 2012a). Silvey et al. (2006) reported that halosulfuron applied PRE, POST, and PRE follow by POST caused 4%, 8%, and 5% injury in snap bean and reduced snap bean yield 11%, 7%, and 15%, respectively.

2.4.2 Weed Control

The primary weed species at the experimental sites were common lambsquarters, wild mustard, redroot pigweed, common ragweed (*Ambrosia artemisiifolia* L.) and green foxtail. Data were pooled across environments (Tables 2-6).

Common Lambsquarters. Halosulfuron, applied PPI, alone and in tankmix with either trifluralin, pendimethalin, EPTC, dimethenamid-*P* or S-metolachlor provided $\geq 96\%$ control of common lambsquarters at 4 and 8 WAE (Table 2.2). Trifluralin, pendimethalin, EPTC and dimethenamid-*P* provided 72 to 87% control of common lambsquarters

control at 4 WAE, but the control declined to 54 to 77% at 8 WAE. S-metolachlor was the least efficacious of the herbicides evaluated for the control of common lambsquarters with 38 and 19% control at 4 and 8 WAE, respectively (Table 2.2). Common lambsquarters density and dry weight reflected the control ratings. Halosulfuron, applied alone reduced common lambsquarters density 98% and biomass 98% compared to the weedy control (Table 2.2). The addition of trifluralin, pendimethalin, EPTC, dimethenamid-*P* or S-metolachlor to halosulfuron did not reduce common lambsquarters density or dry weight compared to halosulfuron applied alone (Table 2.2).

In other studies, trifluralin and S-metolachlor provided 94 and 82% control of common lambsquarters 4 WAE, respectively (Soltani et al. 2014b). The control of common lambsquarters with S-metolachlor decreased to 63% at 8 WAE, however common lambsquarters dry weight was still equivalent to the weedy control (Soltani et al. 2014b). Soltani et al. (2010b) reported 62 and 92% common lambsquarters control with trifluralin applied PPI at two locations. Pendimethalin provides suppression of common lambsquarters (Betts and Morrison 1979; Ferrell et al. 2003; Soltani et al. 2013c). Soltani et al. (2013c) reported 80 to 97% control of common lambsquarters with pendimethalin applied PPI. Halosulfuron applied PRE provided 90 to 98% control of common lambsquarters in pumpkin and applied PPI provided 96 to 100% control of common lambsquarters in white bean (Brown and Masiunas 2002; Soltani et al. 2014a). Halosulfuron, applied POST, does not control common lambsquarters. Halosulfuron and halosulfuron + fomesafen applied POST provided 36 and 57% control of common

lambquarters, respectively (Soltani et al. 2013d).

Wild Mustard. Trifluralin, pendimethalin, EPTC, dimethenamid-*P* or S-metolachlor, applied PPI, provided 3 to 70 and 0 to 27% control of wild mustard at 4 and 8 WAE, respectively (Table 2.3). EPTC and dimethenamid-*P* were the most efficacious with 66 to 70% wild mustard control at 4 WAE, but the control decreased to 24 to 27% at 8 WAE, respectively. Pendimethalin did not control wild mustard $\geq 3\%$ at 4 and 8 WAE, respectively and wild mustard density and dry weight were equivalent to the weedy control. Trifluralin, EPTC, dimethenamid-*P* and S-metolachlor reduced wild mustard density 64, 18, 74 and 53% and wild mustard dry weight 38, 2, 75 and 64%, respectively. Halosulfuron applied alone or in tankmix with trifluralin, pendimethalin, EPTC, dimethenamid-*P* or S-metolachlor controlled wild mustard $\geq 98\%$ and wild mustard density and dry weight was equivalent to the weed-free control (Table 2.3).

Soltani et al. (2014b) reported that trifluralin and S-metolachlor controlled wild mustard 14 and 12% at 8 WAE, respectively and there was no decrease in wild mustard density and dry weight compared to the weedy control which is similar to the results from this study. In addition, Soltani et al. (2014b) reported that halosulfuron, halosulfuron + trifluralin, and halosulfuron + S-metolachlor provided 100% control of wild mustard which is similar to the results in this study. Friesen (1987) in a four year study on weed management in sunflower reported that EPTC provided 33% control of wild mustard which is similar to the results from this study.

Redroot Pigweed. Halosulfuron and halosulfuron tankmixes controlled redroot pigweed 100% at 4 and 8 WAE and there was a 100% reduction in redroot pigweed density and dry weight (Table 2.4). Trifluralin, pendimethalin, dimethenamid-*P* and S-metolachlor controlled redroot pigweed 87 to 97% and 93 to 95% at 4 and 8 WAE, respectively. At 8 WAE, trifluralin, pendimethalin, dimethenamid-*P* and S-metolachlor reduced redroot pigweed density 97, 94, 79 and 88% and redroot pigweed dry weight 97, 93, 92 and 94%, respectively. EPTC applied PPI, averaged 79% control of redroot pigweed at 4 and 8 WAE and reduced density and dry weight 30 and 85%, respectively (Table 2.4).

Soltani et al. (2014b) reported that trifluralin, S-metolachlor, halosulfuron, halosulfuron plus trifluralin and halosulfuron plus S-metolachlor provided 96, 95, 100, 100 and 100% redroot pigweed control at 8 WAE, respectively. Similar results of redroot pigweed control with trifluralin, pendimethalin, EPTC, dimethenamid-*P* and S-metolachlor were reported by Soltani et al. (2012c). Halosulfuron applied POST controlled redroot pigweed 80% (Soltani et al. 2013d).

Common Ragweed. Trifluralin, pendimethalin and S-metolachlor provided 10 to 15% and 1 to 13% control of common ragweed at 4 WAE and 8 WAE, respectively (Table 2.5). EPTC and dimethenamid-*P* controlled common ragweed better than the previous three herbicides, but, did not provide commercially acceptable control with 56 to 62% and 41 to 52% common ragweed control at 4 and 8 WAE, respectively. Halosulfuron and

halosulfuron tankmixes provided ≥ 96 and 91% control of common ragweed at 4 and 8 WAE, respectively. Common ragweed density and biomass with halosulfuron applied alone and in tankmix with trifluralin, pendimethalin, EPTC, dimethenamid-*P* were equivalent to the weed-free control (Table 2.5). The common ragweed density with trifluralin, pendimethalin, EPTC, dimethenamid-*P* and S-metolachlor was equivalent to the weedy control. EPTC decreased common ragweed dry weight 75% (Table 2.5).

Soltani et al. (2014b) reported that halosulfuron, halosulfuron + trifluralin, halosulfuron + S-metolachlor provided 90 to 98% common ragweed control. In another study, halosulfuron controlled common ragweed 91 to 94% (Soltani et al. 2013d). Soltani et al. (2012d) reported that trifluralin, pendimethalin, EPTC, dimethenamid-*P* and S-metolachlor provided 34, 20, 60, 26 and 50% common ragweed control at 8 WAE, respectively.

Green Foxtail. Trifluralin, pendimethalin, EPTC, dimethenamid-*P* and S-metolachlor, applied PPI, provided $\geq 91\%$ green foxtail control (Table 2.6). When the above herbicides were applied in tankmix with halosulfuron there was no improvement in green foxtail control. Halosulfuron, applied PPI, provided 59 and 47% green foxtail control at 4 and 8 WAE, respectively (Table 2.6). Halosulfuron, applied PPI, reduced green foxtail density and dry weight 53 and 67%, respectively. In contrast, the soil-applied grass herbicides, trifluralin, pendimethalin, EPTC, dimethenamid-*P* or S-metolachlor, decreased green foxtail density and biomass $\geq 92\%$.

The poor control of green foxtail with halosulfuron in this study is consistent with other published research. Soltani et al. (2014b) reported that halosulfuron provided 53% and 56% green foxtail control at 4 WAE and 8 WAE, respectively. In addition, Soltani et al. (2014b) found that halosulfuron plus trifluralin and halosulfuron plus S-metolachlor provided 93% control of green foxtail.

2.4.3 White Bean Yield and Seed Moisture Content

The reduced weed interference with all of the herbicide treatments evaluated resulted in white bean yield that was greater than the weedy control (Table 2.1). Reduced weed interference with trifluralin, pendimethalin, EPTC, dimethenamid-*P* and S-metolachlor resulted in an increase in white bean yield of 47, 20, 67, 47 and 47%, respectively (Table 2.1). However, white bean yield with the soil-applied grass herbicides was less than halosulfuron applied alone, halosulfuron tankmixes or the weed-free control. Although the soil-applied grass herbicides provided over 90% annual grass control, annual broadleaf weed control was variable (Tables 2- 6) resulting in reduced white bean yield relative to the weed-free control. White bean yield with halosulfuron applied alone or in tankmix with a soil-applied grass herbicide was equivalent to the weed-free control (Table 2.1). White bean yield with halosulfuron, trifluralin plus halosulfuron, pendimethalin plus halosulfuron, EPTC plus halosulfuron, dimethenamid-*P* plus halosulfuron and S-metolachlor plus halosulfuron was 2.6, 2.6, 2.9, 2.9, 2.7 and 2.9 T ha⁻¹,

respectively which was equivalent to the weed-free control (2.9 T ha^{-1}) (Table 2.1).

2.4.4 Weed emergence

There were no differences between the two permanent quadrats: common lambsquarters ($P=0.9791$), wild mustard ($P=0.4407$), common ragweed ($P=0.6262$), and green foxtail ($P=0.4246$). Therefore the two quadrats samples were combined for further analysis.

Common lambsquarters emergence in the weedy control emerged earlier than with halosulfuron (35 g ai ha^{-1}) applied PPI (Figure 2.1A). Approximately 70% of the cumulative common lambsquarters emergence through the growing season emerged in the first 2 and 3 weeks after white bean emergence in the weedy control and halosulfuron treatment, respectively; indicating delayed common lambsquarters emergence in the halosulfuron treatments (Figure 2.1A). Cumulative common lambsquarters emergence in the weedy control and halosulfuron treatment was 16 and 2 plant m^{-2} , respectively which were significantly different ($P<0.0001$). Halosulfuron, applied PPI at 35 g ai ha^{-1} , reduced common lambsquarters emergence by 75% ($P<0.0001$) (Figure 2.1A).

Wild mustard emergence in the weedy control and halosulfuron treatments followed a similar pattern to common lambsquarters. There was delayed wild mustard emergence in the halosulfuron treatment (Figure 2.1B). Wild mustard emergence, where halosulfuron was applied, was reduced 71% relative to the weedy control ($P<0.0001$) (Figure 2.1B). Cumulative wild mustard emergence in the weedy control and halosulfuron treatment was

21 and 4 plant m⁻², respectively which were significantly different (P=0.0018).

Common ragweed, in contrast to common lambsquarters and wild mustard, emerged earlier from the halosulfuron treatments than the weedy control (Figure 2.1C). However, common ragweed emergence in the halosulfuron treatments was reduced to only 1.3 plants m⁻², which was only 20% of the weedy control (Figure 2.1C). Cumulative common ragweed emergence in the weedy control and halosulfuron treatment was 6.5 and 1.3 plants m⁻², respectively which were significantly different (P<0.0001).

Cumulative green foxtail emergence in the weedy control and halosulfuron treatment was 95 and 60 plants m⁻², respectively which were significantly different (P< 0.001) (Figure 2.1D). However, there was no difference based on green foxtail emergence in the weedy control and halosulfuron treatments (P< =0.69) (Figure 2.1D).

Weed emergence of summer annual broadleaf weeds was reduced with halosulfuron. The weed emergence values are consistent with the control, density and biomass data. The application of halosulfuron delayed the emergence of common lambsquarters and wild mustard, but halosulfuron had no effect on the emergence pattern of green foxtail and resulted in earlier emergence of common ragweed. Overall, the cumulative weed emergence is corroborated by the white bean yield data. The delay in weed emergence in the halosulfuron plots versus the weedy plots was the result of the pre-emergence residual activity of halosulfuron. This is corroborated by the lack of difference in emergence timing for green foxtail. The delay in emergence in the halosulfuron plots may have been caused by the pre-emergence residual activity of halosulfuron forcing a greater proportion

of seedlings to emerge from greater soil depth, which is known to delay weed seedling emergence (Bullied et al. 2003).

2.5 Conclusions

The results of this study conclude that there is an adequate margin of crop safety in white bean to PPI application of trifluralin, pendimethalin, EPTC, dimethenamid-*P* or S-metolachlor applied alone or in tankmix with halosulfuron. Trifluralin, pendimethalin, EPTC, dimethenamid-*P* or S-metolachlor plus halosulfuron provided full season control of common lambsquarters, wild mustard, redroot pigweed, common ragweed and green foxtail. White bean yield was equivalent to the weed-free control with the above herbicide tankmixes. The registration of trifluralin, pendimethalin, EPTC, dimethenamid-*P* or S-metolachlor plus halosulfuron applied PPI will provide broad spectrum weed control in white bean with an adequate margin of crop safety.

Table 2.1. White bean injury (visual rating) 1 and 4 weeks after emergence (WAE), seed moisture content and yield with halosulfuron alone and in tankmix with soil-applied grass herbicides applied PPI at Exeter (2013-2014) and Ridgetown, ON, Canada (2014).

Herbicide treatment	Rate (g ai ha ⁻¹)	Injury		Seed Moisture Content (%)	Yield (T ha ⁻¹)
		1 WAE	4 WAE		
		(%)			
Weedy control		0 ^z a	0a	19.7	1.5f
Weed-free control		0a	0a	19.1	2.9a
Trifluralin	600	0a	0ab	18.7	2.2d
Pendimethalin	1080	0a	0a	19.4	1.8e
EPTC	3400	0a	0a	18.7	2.5bc
Dimethenamid- <i>P</i>	544	1b	1abc	19.4	2.2cd
<i>S-metolachlor</i>	1050	0a	0abc	19.0	2.2d
Halosulfuron	35	0a	0abc	19.0	2.6ab
Trifluralin + halosulfuron	600 + 35	1b	1c	19.1	2.6ab
Pendimethalin + halosulfuron	1080 + 35	0a	0abc	19.3	2.9a
EPTC + halosulfuron	3400 + 35	0a	1abc	18.8	2.9a
Dimethenamid- <i>P</i> + halosulfuron	544 + 35	2b	2d	19.5	2.7ab
<i>S-metolachlor</i> + halosulfuron	1050 + 35	1a	1bc	18.8	2.9a
P-value		0.01	0.03	0.08	<0.001

^zData were pooled across all experiments that were conducted at 6 sites during 2013 and 2014.

Table 2.2. Common lambsquarters control (based on visual rating), density, and above ground dry weight in white bean treated with halosulfuron alone and in tankmix with soil-applied grass herbicides applied PPI at Exeter (2013-2014) and Ridgetown, ON, Canada (2014).

Herbicide treatment	Rate (g ai ha ⁻¹)	Control		Density (plants m ⁻²)	Above ground dry weight (g m ⁻²)
		4 WAE	8 WAE		
		(%)			
Weedy control		0 ^z d	0d	11.9e	11.2e
Weed-free control		100a	100a	0.0a	0.0a
Trifluralin	600	79b	60b	2.5d	1.3bc
Pendimethalin	1080	74b	54b	2.6d	2.5cd
EPTC	3400	87b	77b	2.0cd	1.7c
Dimethenamid- <i>P</i>	544	72b	55b	2.3d	2.0cd
<i>S-metolachlor</i>	1050	38c	19c	3.1d	4.7d
Halosulfuron	35	98a	97a	0.8bc	0.3ab
Trifluralin + halosulfuron	600 + 35	99a	99a	0.2ab	0.1ab
Pendimethalin + halosulfuron	1080 + 35	99a	100a	0.4ab	0.4ab
EPTC + halosulfuron	3400 + 35	100a	100a	0.2ab	0.1a
Dimethenamid- <i>P</i> + halosulfuron	544 + 35	100a	99a	0.3ab	0.4ab
<i>S-metolachlor</i> + halosulfuron	1050 + 35	100a	99a	0.3ab	0.2ab
P-value		<0.001	<0.001	<0.001	<0.001

^zData were pooled across all experiments that were conducted at 6 sites during 2013 and 2014.

Table 2.3. Wild mustard control (based on visual ratings), density, and above ground dry weight in white bean with halosulfuron alone and in tankmix with soil-applied grass herbicides applied PPI at Exeter (2013-2014) and Ridgetown, ON, Canada (2014).

Herbicide treatment	Rate (g ai ha ⁻¹)	Control		Density (plants m ⁻²)	Above ground dry weight (g m ⁻²)
		4 WAE	8 WAE		
		(%)			
Weedy control		0 ^{ze}	0c	33.1b	19.8d
Weed-free control		100a	100a	0.0a	0.0a
Trifluralin	600	28c	11b	11.7b	12.3bcd
Pendimethalin	1080	3d	0c	27.8b	28.7d
EPTC	3400	66b	24b	27.0b	15.0cd
Dimethenamid- <i>P</i>	544	70b	27b	8.3b	4.9b
<i>S-metolachlor</i>	1050	55b	11b	15.5b	7.1bc
Halosulfuron	35	100a	100a	0.0a	0.0a
Trifluralin + halosulfuron	600 + 35	100a	100a	0.0a	0.0a
Pendimethalin + halosulfuron	1080 + 35	100a	99a	0.0a	0.0a
EPTC + halosulfuron	3400 + 35	100a	100a	0.1a	0.1a
Dimethenamid- <i>P</i> + halosulfuron	544 + 35	100a	100a	0.0a	0.0a
<i>S-metolachlor</i> + halosulfuron	1050 + 35	100a	100a	0.1a	0.0a
P-value		<0.001	<0.001	<0.001	<0.001

^zData were pooled across all experiments that were conducted at 6 sites during 2013 and 2014.

Table 2.4. Redroot pigweed control (based on visual ratings), density, and above ground dry weight in white bean with halosulfuron alone and in tankmix with soil-applied grass herbicides applied PPI at Exeter (2013-2014) and Ridgetown, ON, Canada (2014).

Herbicide treatment	Rate (g ai ha ⁻¹)	Control		Density (plants m ⁻²)	Above ground dry weight (g m ⁻²)
		4 WAE	8 WAE		
		(%)			
Weedy control		0 ^z d	0d	3.3c	9.1
Weed-free control		100a	100a	0.0a	0.0
Trifluralin	600	96ab	95ab	0.1a	0.2
Pendimethalin	1080	91bc	93bc	0.2a	0.6
EPTC	3400	79c	78c	2.3bc	1.4
Dimethenamid- <i>P</i>	544	97ab	93bc	0.7ab	0.7
<i>S-metolachlor</i>	1050	87bc	93bc	0.4ab	0.5
Halosulfuron	35	100a	100a	0.0a	0.0
Trifluralin + halosulfuron	600 + 35	100a	100a	0.0a	0.0
Pendimethalin + halosulfuron	1080 + 35	100a	100ab	0.0a	0.0
EPTC + halosulfuron	3400 + 35	100a	100ab	0.0a	0.0
Dimethenamid- <i>P</i> + halosulfuron	544 + 35	100a	100a	0.0a	0.0
<i>S-metolachlor</i> + halosulfuron	1050 + 35	100a	100a	0.0a	0.0
P-value		0.0007	0.0049	0.0226	0.0555

^zData were pooled across all experiments that were conducted at 6 sites during 2013 and 2014.

Table 2.5. Common ragweed control (based on visual ratings), density, and above ground dry weight in white bean with halosulfuron alone and in tankmix with soil-applied grass herbicides applied PPI at Exeter (2013-2014) and Ridgetown, ON, Canada (2014).

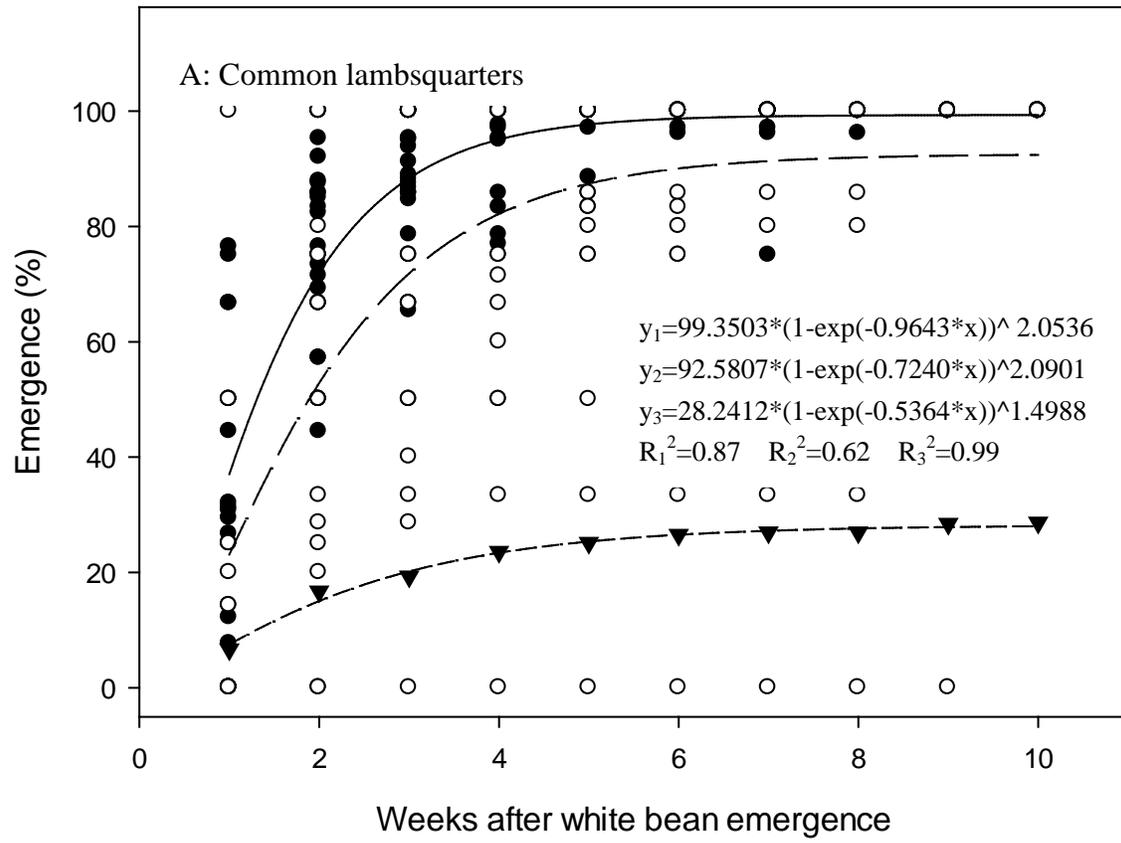
Herbicide treatment	Rate (g ai ha ⁻¹)	Control		Density (plants m ⁻²)	Above ground dry weight (g m ⁻²)
		4 WAE	8WAE		
		(%)			
Weedy control		0 ^z d	0e	5.7b	10.4d
Weed-free control		100a	100a	0.0a	0.0a
Trifluralin	600	14c	9d	4.2b	12.4d
Pendimethalin	1080	10c	1e	5.7b	9.1d
EPTC	3400	62b	52c	3.8b	2.6c
Dimethenamid- <i>P</i>	544	56b	41c	3.5b	7.2d
<i>S-metolachlor</i>	1050	15c	13d	6.0b	8.8d
Halosulfuron	35	97a	95b	0.5a	0.3ab
Trifluralin + halosulfuron	600 + 35	97a	95b	0.6a	0.7abc
Pendimethalin + halosulfuron	1080 + 35	98a	92b	0.4a	0.6ab
EPTC + halosulfuron	3400 + 35	99a	97ab	0.3a	0.3ab
Dimethenamid- <i>P</i> + halosulfuron	544 + 35	99a	97ab	0.7a	0.7ab
<i>S-metolachlor</i> + halosulfuron	1050 + 35	98a	95b	0.4a	1.4bc
P-value		<0.001	<0.001	<0.001	<0.001

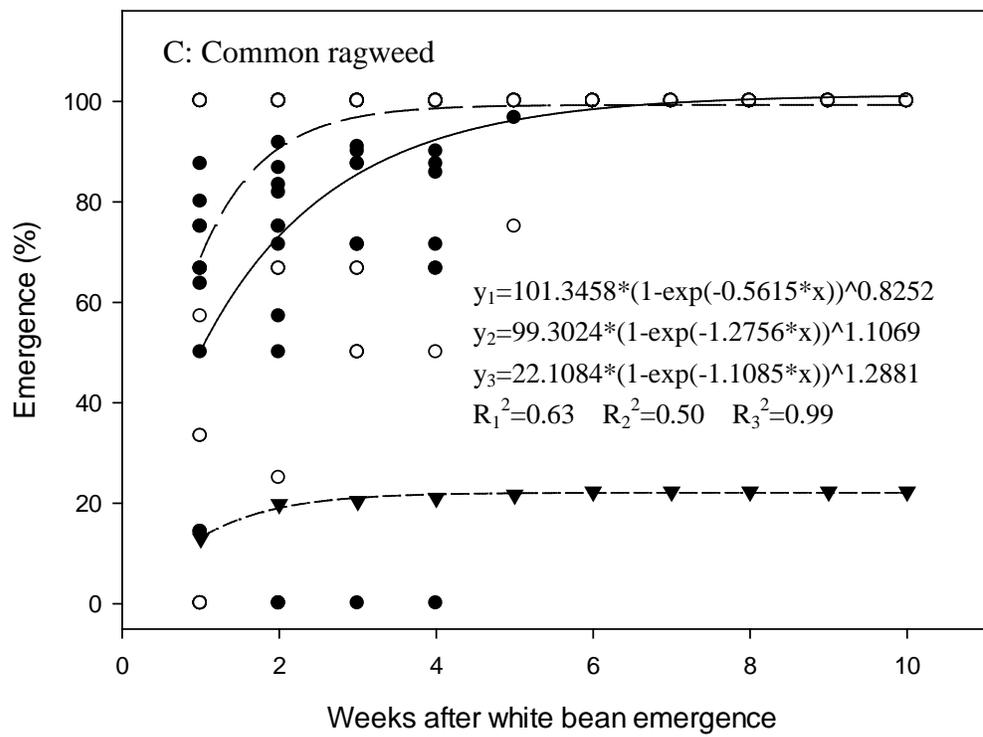
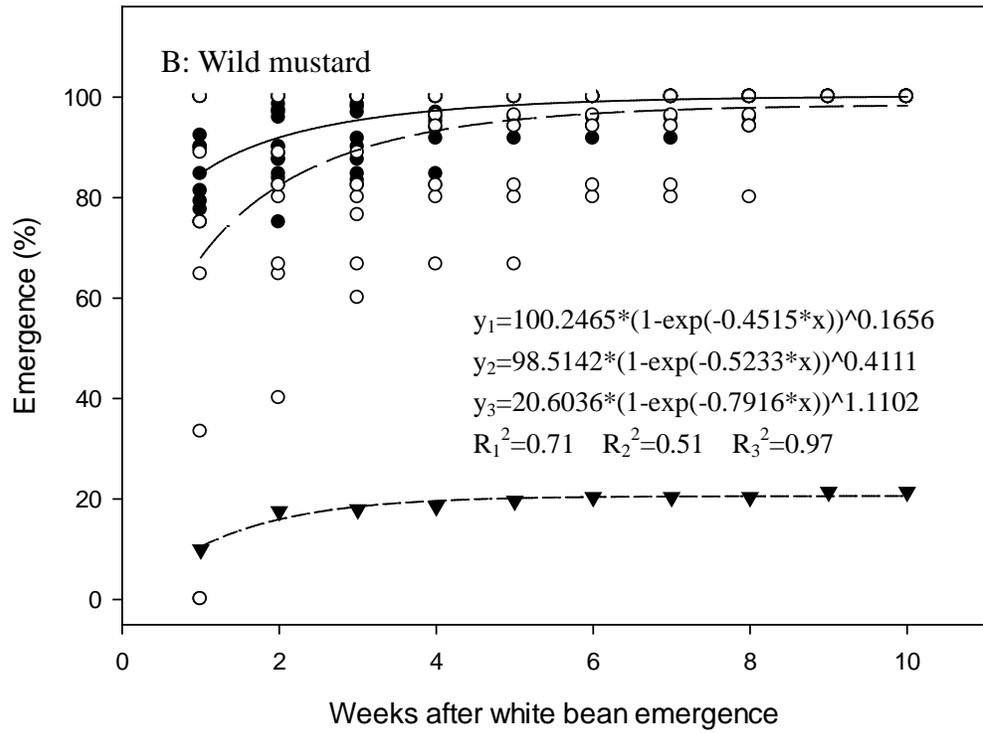
^zData were pooled across all experiments that were conducted at 6 sites during 2013 and 2014.

Table 2.6. Green foxtail control (based on visual ratings), density, and above ground dry weight in white bean with halosulfuron alone and in tankmix with soil-applied grass herbicides applied PPI at Exeter (2013-2014) and Ridgetown, ON, Canada (2014).

Herbicide treatment	Rate (g ai ha ⁻¹)	Control		Density (plants m ⁻²)	Above ground dry weight (g m ⁻²)
		4 WAE	8 WAE		
		(%)			
Weedy control		0 ^z e	0e	36.2d	42.3d
Weed-free control		100a	100a	0.0a	0.0a
Trifluralin	600	94bc	94bc	2.0b	2.6b
Pendimethalin	1080	92c	93bc	2.8b	3.2b
EPTC	3400	96b	94bc	1.7b	2.3b
Dimethenamid- <i>P</i>	544	96bc	95b	1.8b	1.6b
<i>S-metolachlor</i>	1050	93bc	94bc	2.5b	2.7b
Halosulfuron	35	59d	47d	16.9c	13.8c
Trifluralin + halosulfuron	600 + 35	94bc	92bc	2.3b	2.8b
Pendimethalin + halosulfuron	1080 + 35	92bc	91c	2.0b	2.4b
EPTC + halosulfuron	3400 + 35	95bc	94bc	2.6b	2.2b
Dimethenamid- <i>P</i> + halosulfuron	544 + 35	96bc	93bc	2.3b	2.6b
<i>S-metolachlor</i> + halosulfuron	1050 + 35	94bc	93bc	2.3b	1.9b
P-value		<0.001	<0.001	<0.001	<0.001

^zData were pooled across all experiments that were conducted at 6 sites during 2013 and 2014.





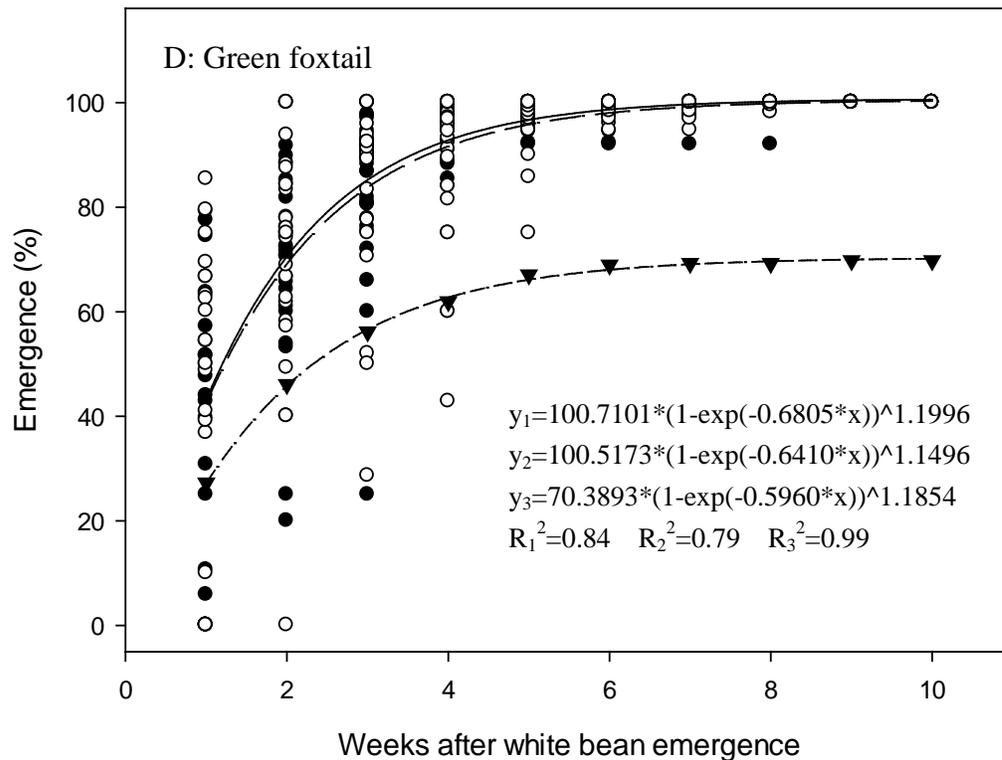


Figure 2.1. Emergence periodicity of common lambsquarters (A), wild mustard (B), common ragweed (C), and green foxtail (D) in white bean with influence and without influence by halosulfuron. (●, —) and y_1 represents the emergence of weeds in weedy control based on final accumulative weeds in weedy control; (○, — —) and y_2 represents the emergence of weeds in halosulfuron treatment based on final accumulative weeds in halosulfuron treatment; (▼, - - -) and y_3 represents the emergence of weeds in halosulfuron based on final accumulative weeds in weedy control.

Chapter 3: Halosulfuron Tankmixes Applied PRE in White Bean

This chapter is a modified version of the following manuscript published in *Weed Technology*.

Li, Z., R. Van Acker, D. E. Robinson, N. Soltani, and P. H. Sikkema. 2016. Halosulfuron tank-mixes applied PRE in white bean. *Weed Technology*. 30:57-66.

3.1 Abstract

White bean tolerance and weed control were examined by applying halosulfuron alone or in combination with pendimethalin, dimethenamid-*P* or S-metolachlor applied preemergence (PRE). All herbicides applied alone or in combination caused $\leq 3\%$ visible injury 1 and 4 weeks after emergence (WAE) in soil with soil organic matter from 2.9 to 4.7% and soil pH from 7.1 to 7.8. Halosulfuron applied PRE provided $\geq 95\%$ control of common lambsquarters, wild mustard, redroot pigweed and common ragweed and $\leq 55\%$ control of green foxtail at 4 and 8 WAE. Weed density and dry weight at 8 WAE paralleled the control ratings. Dry bean yields from plots treated with halosulfuron plus a soil-applied grass herbicide combinations did not differ from the weed free control. Green foxtail competition with white bean in halosulfuron PRE applied alone resulted in reduced white bean yield compared to the weed-free control.

3.2 Introduction

White bean (*Phaseolus vulgaris* L.) is the major dry edible bean produced in Ontario, with 58, 55 and 48% of total dry edible bean production in 2012, 2013 and 2014, respectively (Statistics Canada 2015). Ontario is the largest white bean producer in Canada, with 77% of Canadian white bean production in 2014 (Kumuduni 2014; Statistics Canada 2015). White bean is susceptible to weed interference with 77, 58, 81 and 68% yield loss due to weed interference in studies by Malik et al. 1993, Chikoye et al. 1995, Soltani et al. 2014b and Soltani et al. 2014c, respectively.

There were only three herbicides registered in Ontario for broadleaf weed control in white bean including imazethapyr, bentazon and fomesafen when this study was initiated (OMAFRA 2012; PMRA 2010; Sikkema et al. 2004a). Bentazon and fomesafen are applied POST (Sikkema et al. 2004a) while imazethapyr was the only soil-applied broadleaf herbicide available for use on white bean in 2013. Although, imazethapyr is an efficacious soil-applied herbicide with activity on both annual grass and broadleaf weeds, it has a narrow margin of crop safety in white bean (Arnold et al. 1993; Bauer et al. 1995; Blackshaw and Saindon 1996; Soltani et al. 2007; Wilson and Miller 1991). Halosulfuron, which was registered for use in Ontario in 2014, provides an additional herbicide option for the control of annual broadleaf weeds, including common lambsquarters, redroot pigweed, velvetleaf, wild mustard, common cocklebur (*Xanthium strumarium* L.), jimsonweed and lady's thumb (Senseman 2007). In contrast, halosulfuron provides little to no control of annual grass weeds including green foxtail and barnyard grass

(*Echinochloa crus-galli* P.Beauv.) (Senseman 2007). For example, Soltani et al. (2014b) reported only 50% control of green foxtail with halosulfuron applied preplant incorporated (PPI). Halosulfuron soil adsorption is correlated with soil organic carbon content and inversely related to soil pH (Dermiyati and Yamamoto 1997a). Halosulfuron is degraded by microbial degradation and through chemical hydrolysis. It will hydrolyze more rapidly when soil pH is less than 4.5 (Grey et al. 2007). Higher soil pH and lower soil organic matter will result in greater crop injury. The low rate of halosulfuron (35 g ai ha⁻¹) is recommended for light textured, low organic matter soils (Senseman 2007).

There are three soil-applied PRE herbicides that have activity on annual grasses that may have an adequate margin of crop safety in white bean in Ontario: pendimethalin, dimethenamid-*P* and S-metolachlor, with only S-metolachlor being currently registered for use on white bean. Pendimethalin, a Group 3 dinitroaniline herbicide, controls many annual grass weeds including large crabgrass, barnyard grass, and green foxtail (Senseman 2007; Soltani et al. 2012a). In addition, pendimethalin provides suppression of common lambsquarters (Betts and Morrison 1979; Ferrell et al. 2003; Soltani et al. 2013c). Dimethenamid-*P* and S-metolachlor are Group 15 chloroacetamide herbicides that control emerging annual grass weeds and suppress some small seeded broadleaf weeds including eastern black nightshade, common lambsquarters and pigweed species (*Amaranthus spp.*) (Senseman 2007; Soltani et al. 2012a). Soltani et al. (2012a), for example, reported that pendimethalin, dimethenamid-*P* and S-metolachlor applied PPI provided greater than 95% control of green foxtail.

Halosulfuron applied in combination with pendimethalin, dimethanamid-*P* or S-metolachlor applied PRE may provide control of many common annual grasses and broadleaf weeds in white bean in Ontario. The registration of these PRE tankmixes would provide Ontario white bean producers with an additional weed management option that provides broad spectrum weed control with adequate crop safety. The objective of this research was to evaluate the level of crop injury, weed control, weed emergence timing, and white bean yield when halosulfuron was applied PRE alone or in combination with pendimethalin, dimethanamid-*P* or S-metolachlor.

3.3 Materials and Methods

Six field experiments were conducted over a two-year period (2013, 2014), including four trials at the University of Guelph's Huron Research Station near Exeter, Ontario, Canada (2013, 2014) and two trials at the University of Guelph's Ridgetown Campus near Ridgetown, Ontario, Canada (2014).

The soils for the two trials near Exeter in 2013 were a Brookston clay loam with 29% sand, 44% silt, 27% clay, 3.6% organic matter and pH of 7.7 at site 1 and 18% sand, 46% silt, 36% clay, 4.7% organic matter and pH of 7.5 at site 2. The soils for the two trials near Exeter in 2014 were 31% sand, 42% silt, 27% clay, 3.8% organic matter and pH of 7.7 at site 3 and 41% sand, 40% silt, 19% clay, 3.3% organic matter and pH of 7.7 at site 4. The soils for the two trials near Ridgetown in 2014 were a Fox sandy loam with 50% sand, 25% silt, 25% clay, 2.9% organic matter and pH of 7.1 for site 5 and 45% sand, 26%

silt, 29% clay, 3.7% organic matter and pH of 7.8 for site 6. Seedbed preparation consisted of fall moldboard plowing followed by two passes with a field cultivator with rolling basket harrows in the spring.

All six experiments were conducted as a randomized complete block design with four replications. Herbicides evaluated included halosulfuron (Gowan Canada, P.O. Box 248, Station T, Calgary, AB, Canada) alone or in combination with pendimethalin (BASF Canada Inc., 100 Milverton Drive, 5th Floor, Mississauga, ON, Canada), dimethenamid-*P* (BASF Canada Inc., 100 Milverton Drive, 5th Floor, Mississauga, ON, Canada) or S-metolachlor (Syngenta Canada Inc., 140 Research Lane, Guelph, ON, Canada), applied PRE as listed in Table 3.1. White bean ('T9905') (Thompsons Limited, Hensall, ON) was seeded at 250,000 seeds ha⁻¹ to a depth of 4 cm in late May to early June of each year depending on weather conditions. Each plot was 3 m wide consisting of four rows (spaced 0.75 m apart) and 10 or 8 m in length at the Exeter and Ridgetown sites, respectively.

Herbicides were applied after seeding and before the white bean plants emerged. Depending on the weather, herbicides were applied within 8 days after planting. Beans were planted on May 27th and June 6th, 2013 for site 1 and 2 near Exeter, respectively. Herbicides were sprayed on June 4th and 14th for site 1 and 2, respectively. In 2014, beans were planted on June 2nd, 9th, 6th and 18th for site 3 to 6 near Exeter and Ridgetown, respectively. Herbicides were sprayed on June 10th, 16th, 13th and 24th for site 3 to 6, respectively. Herbicides were applied with a CO₂ pressurized backpack sprayer calibrated

to deliver 200 L ha⁻¹ of spray solution at a pressure of 200 kPa using ULD 120-02 (Hypro, New Brighton, MN) ultra low drift nozzles. The spray boom was 1.5 m in length with four nozzles spaced 50 cm apart.

White bean injury was visually estimated on a scale of 0 (no injury) to 100% (complete plant death) at 1 and 4 weeks after emergence (WAE). Weed control was visually estimated on a scale of 0 (no control) to 100% (complete control) at 4 and 8 WAE. Weed density and dry weight were determined 8 WAE by cutting the weeds at the soil surface in two 0.5 m² quadrats per plot and separating and counting by species. Data from the two quadrats in each plot was combined for analysis. Weeds were dried at 60 C to a constant weight and then weighed. White bean plants from the center two rows of each plot was harvested using a plot scale combine harvester when 90% of the pods in the weed-free control were golden in color. White bean weight and moisture content were recorded per plot and yields were adjusted to 18% seed moisture content.

Data were subjected to an analysis of variance using the PROC MIXED procedures of SAS version 9.3 (SAS Institute Inc., Cary, NC). Herbicide treatment was considered a fixed effect, while location, block within location, and their interactions were considered random effects. Significance of fixed effects were tested using F-tests and random effects were tested using a Z-test of the variance estimate. The UNIVARIATE procedure was used to test data for normality and homogeneity of variance. Any treatment assigned a value of zero was excluded from the analysis including: the weedy and weed free control for injury; and the weed free control for weed control, weed density and weed dry weight.

Significant differences among treatments evaluated was determined using the Tukey adjusted means comparison with differences considered significant at $p < 0.05$.

Weed emergence data was collected weekly from 1 to 10 WAE from two 0.25 m² permanent quadrats in the weedy control and halosulfuron treatment plots. Data from the two quadrats was analyzed by PROC MIXED to determine if there were differences and then they were combined for analysis. The percent of accumulated weed emergence in weedy control and halosulfuron treated plots was based on the total weed emergence in the weedy control and halosulfuron treated plots, respectively. Weed emergence curves were obtained by nonlinear regression using the sigmoidal equation:

$$y = a(1 - e^{-bx})^c$$

where y represents the percent of total accumulated weed emergence at weeks after white bean emergence x , e is the base of the natural logarithm, and a , b , c are the parameters. The curves were plotted in SigmaPlot v. 12.1 (Systat Software Inc., Chicago, USA). The difference in weed emergence in the weedy control compared to halosulfuron treatments was analyzed by a two sample t-test in SAS version 9.3. The mean comparison of two treatments was also tested. The percent emergence of weeds in the halosulfuron treated plots was based on final accumulative weeds in weedy control is also presented in Figure 3.1. However, the model we used could not fit to those data due to very high weed emergence in the first week.

3.4 Results and Discussion

3.4.1 Crop Injury

White bean injury caused by the applied herbicides is presented in Table 3.1. Data were pooled across environments. Pendimethalin, halosulfuron and pendimethalin plus halosulfuron caused no injury in white bean at 1 and 4 weeks after emergence (WAE). Dimethenamid and S-metolachlor caused 3 and 2% white bean injury at 1 WAE and 1 and 0% injury at 4 WAE, respectively. The level of white bean injury with dimethenamid and S-metolachlor did not increase with the addition of halosulfuron. At 1 WAE, dimethenamid-*P* and dimethenamid-*P* plus halosulfuron caused the greatest injury to white bean (Table 3.1). At 4 WAE, the applied herbicides caused $\leq 1\%$ in white bean and there was no difference among the herbicides evaluated (Table 3.1). Dimethenamid-*P* (440 g ai ha⁻¹) applied PRE caused 2, 1, and 0% dry bean injury at 1, 2, 4 WAE, respectively (Soltani et al. 2014a). When soil was sandy (86%) low organic matter (1%), dimethenamid-*P* (1300 g ai ha⁻¹) and S-metolachlor (2800 g ai ha⁻¹) applied PRE damaged white bean cultivars without seed yield reduction (Poling et al. 2009). The level of injury from halosulfuron in this study is similar to a study by Soltani et al. (2014c) who reported no white bean injury with halosulfuron applied PRE at 35 g ai ha⁻¹. In addition, Soltani et al. (2014c) reported that halosulfuron applied PPI or PRE resulted in less white bean injury than when it was applied POST. In another study, S-metolachlor at 1600 and 3200 g ai ha⁻¹ applied PRE did not cause any white bean injury or white bean

plant height reduction (Soltani et al. 2004b). However, in that same study, the addition of clomazone (1680 g ai ha⁻¹) to S-metolachlor (3200 g ai ha⁻¹) caused a decrease in white bean height of 18%. Soltani et al. (2013b) reported pendimethalin applied PRE caused more injury than when it was applied PPI at 4 WAE to selected dry bean market classes including white bean, but the injury to white bean was as low as 1%. Overall, this study concludes that pendimethalin, dimethenamid-*P*, S-metolachlor and halosulfuron, applied alone, or in combination resulted in little, to no, white bean injury, which was similar to the results observed in other studies.

3.4.2 Weed Control

Common lambsquarters, wild mustard, redroot pigweed, common ragweed and green foxtail were the dominant weeds at the experimental sites. Data were pooled across sites. The results are presented in Tables 3.2-3.6.

Common Lambsquarters. At 4 and 8 WAE, halosulfuron (35 g ai ha⁻¹) or pendimethalin (1080 g ai ha⁻¹) applied PRE provided excellent common lambsquarters control (95 to 98%) while dimethenamid-*P* and S-metolachlor provided poor common lambsquarters control (9 to 52%) (Table 3.2). Halosulfuron applied PRE in combination with pendimethalin, dimethenamid-*P* or S-metolachlor controlled common lambsquarters 98 to 100% at 4 and 8 WAE. Common lambsquarters density and dry weight at 8 WAE followed a similar pattern. Halosulfuron reduced common lambsquarters density and dry

weight 96 and 99%, respectively (Table 3.2). Addition of pendimethalin, dimethenamid-*P* or S-metolachlor to halosulfuron did not improve the control of common lambsquarters (Table 3.2).

Excellent control of lambsquarters with halosulfuron and pendimethalin applied PRE has been reported in other studies. Brown and Masiunas (2002) reported that halosulfuron applied PRE provided 90 to 98% control of common lambsquarters in a study conducted in pumpkin (*Cucurbita* spp.). In previous white bean field studies, halosulfuron provided 95 to 100%, 83 to 99%, and 36 to 51% common lambsquarters control when halosulfuron was applied PPI, PRE, and POST, respectively (Soltani et al. 2013d; Soltani et al. 2014b; Soltani et al. 2014c). Chomas and Kells (2004) found that pendimethalin applied PRE provided almost 100% control of triazine-resistant common lambsquarters. In that same study, metolachlor provided 66% control of triazine-resistant common lambsquarters. Dimethenamid-*P* applied PRE provided 80% common lambsquarters control in a study conducted in potato (*Solanum tuberosum*) (Hutchinson et al. 2005). Although, dimethenamid-*P* and S-metolachlor provided good common lambsquarters control in other studies, in this study, dimethenamid-*P* and S-metolachlor reduced common lambsquarters dry weight by only 67 and 55%, respectively (Table 3.2). Common lambsquarters dry weight with S-metolachlor applied PRE was equivalent to the weedy control (Table 3.2). In a greenhouse study, Isaacs et al. (2006) reported less than 1% control of common lambsquarters with POST applications of halosulfuron.

Wild Mustard. Halosulfuron (35 g ai ha⁻¹) applied PRE provided excellent control of wild mustard. Halosulfuron, applied alone, or in combination with either pendimethalin, dimethenamid-*P* or S-metolachlor provided greater than 97% wild mustard control at 4 and 8 WAE and a 100% reduction in wild mustard density and dry weight (Table 3.3). At 4 WAE, pendimethalin, dimethenamid-*P* and S-metolachlor applied alone provided 48, 57 and 50% control of wild mustard, respectively. Wild mustard control decreased over time with only 7-39% control at 8 WAE (Table 3.3). Wild mustard density and dry weight with pendimethalin, dimethenamid-*P* and S-metolachlor was equivalent to the weedy control.

In other studies, S-metolachlor, applied PPI, provided 12% wild mustard control at 8 WAE, and no decrease in wild mustard dry weight and density compared to the weedy control (Soltani et al. 2014b). Pendimethalin provided poor control of broadleaf weeds including wild mustard (Senseman 2007). Soltani et al. (2014c) reported that halosulfuron (35 g ai ha⁻¹) applied PPI, PRE or POST provided 99 to 100% wild mustard control. Soltani et al. (2014b) also reported that, halosulfuron + S-metolachlor, applied PPI, provided 100% wild mustard control which is identical to what was observed in this study.

Redroot Pigweed. Dimethenamid-*P* (544 g ai ha⁻¹), S-metolachlor (1050 g ai ha⁻¹) or halosulfuron (35 g ai ha⁻¹), applied PRE alone or in combination, provided almost 100% control of redroot pigweed at 4 and 8 WAE (Table 3.4). These same treatments reduced

redroot pigweed density and dry weight 99-100%. Pendimethalin (1080 g ai ha⁻¹) applied PRE provided 69 and 67% control of redroot pigweed at 4 and 8 WAE, respectively. Pendimethalin, applied PRE, reduced redroot pigweed density and dry weight 64 and 77%, respectively (Table 3.4).

Soltani et al. (2012c) reported 73-76% redroot pigweed control with pendimethalin, which was similar to the findings in this study (Table 3.4). In subsequent studies they found that halosulfuron applied PPI and PRE provided 97% redroot pigweed control at 8 WAA, but control was reduced to 80% when applied POST (Soltani et al. 2013d; Soltani et al. 2014b). S-metolachlor applied PRE provided 87 to 91% control of redroot pigweed in a field study in kidney bean (Soltani et al. 2014d). Soltani et al. (2014b) also found that S-metolachlor plus halosulfuron applied PPI provided 100% redroot pigweed control at 8 WAE, the same result as found in this study.

Common Ragweed. Pendimethalin (1080 g ai ha⁻¹) and S-metolachlor (1050 g ai ha⁻¹) applied PRE provided 9 to 11% and 2 to 3% control of common ragweed at 4 and 8 WAE, respectively (Table 3.5). Pendimethalin reduced common ragweed density and dry weight 42 and 35%, respectively; while S-metolachlor reduced common ragweed density and dry weight 60 and 42%, respectively. Dimethenamid-*P* (544 g ai ha⁻¹) applied PRE provided 41 and 19% control at 4 and 8 WAE, respectively, and reduced common ragweed density and dry weight by 76 and 68%, respectively (Table 3.5). Halosulfuron, applied PRE, provided 96% control of common ragweed, and reduced common ragweed density and

dry weight 96 and 98%, respectively. Addition of pendimethalin, dimethenamid-*P* or S-metolachlor to halosulfuron did not improve the control of common ragweed.

Soltani et al. (2014b) reported 30 to 40% common ragweed control with S-metolachlor and 97 to 99% control with halosulfuron applied PPI. Halosulfuron, applied POST, provided 91 to 94% common ragweed control (Soltani et al. 2013d). The excellent control of common ragweed with halosulfuron applied PRE in this study is consistent with previous studies.

Green Foxtail. Pendimethalin (1080 g ai ha⁻¹), dimethenamid-*P* (544 g ai ha⁻¹) or S-metolachlor (1050 g ai ha⁻¹) applied PRE alone or in combination with halosulfuron provided 90-99% and 88-94% green foxtail control at 4 and 8 WAE, respectively. In addition these treatments reduced green foxtail density and dry weight by 89-97% and 93-99%, respectively (Table 3.6). Halosulfuron (35 g ai ha⁻¹), applied PRE did not provide adequate green foxtail control. Halosulfuron provided 35 and 53% control at 4 and 8 WAE, respectively; and reduced green foxtail density and dry weight 49 and 72%, respectively (Table 3.6). The addition of halosulfuron to pendimethalin, dimethenamid-*P* or S-metolachlor did not decrease the efficacy of these herbicides on green foxtail. Soltani et al. (2014b) reported 56% green foxtail control with halosulfuron applied PPI but there was no decrease in green foxtail density and dry weight in a study conducted in white bean. In that same study, S-metolachlor provided 95 and 97% green foxtail control at 4 and 8 WAE, with a 93 and 96% density and dry weight reduction, respectively.

3.4.3 Weed Emergence

There were no differences in weed emergence between the two quadrats for common lambsquarters ($P=0.7552$), wild mustard ($P=0.2732$), common ragweed ($P=0.3509$), and green foxtail ($P=0.6087$). Therefore the data from the two quadrats were combined for further analysis. Halosulfuron (35 g ai ha^{-1}), applied PRE delayed common lambsquarters emergence compared to the weedy control (Figure 3.1A) ($P=0.001$). In the weedy control, approximately 90% of the common lambsquarters emerged by 3 weeks after white bean emergence (WAE), while in the halosulfuron treatment, 90% common lambsquarters emergence did not occur until 5 WAE. Cumulative common lambsquarters emergence in the weedy control and the halosulfuron treatment was 22 and 4 plants m^{-2} , respectively, which was significantly different ($P<0.0001$) between these two treatments.

Halosulfuron (35 g ai ha^{-1}), applied PRE delayed wild mustard emergence relative to the weedy control (Figure 3.1B) ($P=0.0063$). The cumulative wild mustard emergence in the weedy control and the halosulfuron treated plots was 22 and 3 plants m^{-2} , respectively; and this difference was significant ($P<0.0001$).

Halosulfuron (35 g ai ha^{-1}), applied PRE delayed common ragweed emergence relative to the weedy control (Figure 3.1C) ($P=0.001$). Ninety percent common ragweed emergence occurred at 2 and 5 WAE in the weedy control and halosulfuron treated plots, respectively (Figure 3.1C). The cumulative common ragweed emergence in the weedy

control and the halosulfuron treated plots was 8 and 2 plants m^{-2} , respectively ($P < 0.0001$).

Halosulfuron (35 g ai ha^{-1}), applied PRE had no effect on green foxtail emergence timing (Figure 3.1D) ($P = 0.40$). The cumulative green foxtail emergence in the weedy control and in the halosulfuron treated plots was 104 and 88 plants m^{-2} , respectively, and that difference was not statistically significant ($P = 0.08$).

Halosulfuron, applied PRE caused a delay in broadleaf weed emergence relative to the weedy control. However, halosulfuron did not have an impact on green foxtail emergence timing. These data parallel the weed control, weed density and dry weight results indicating that halosulfuron provides control of common annual broadleaf weeds (common lambsquarters, wild mustard, redroot pigweed and common ragweed) but has little to no activity on green foxtail. These results demonstrate the direct (reduced weed density) and indirect (delayed emergence timing) of halosulfuron on these common broadleaf weeds. The indirect effect can be important for crops like white bean which have a long delay in canopy closure (Van Acker et al. 2000).

3.4.4 White Bean Seed Moisture Content and Yield

The presence of weeds delayed white bean maturity as indicated by the increased seed moisture content in the weedy control relative to the weed-free control (Table 3.7). There was no advancement in white bean maturity with the application of pendimethalin,

dimethenamid-*P* or S-metolachlor. Halosulfuron, applied PRE, advanced the maturity of white bean compare to the weedy control (as measured by seed moisture content at harvest), but maturity was still delayed compared to the weed-free control (Table 3.7). The application of pendimethalin, dimethenamid-*P* or S-metolachlor combined with halosulfuron resulted in no effect on white bean maturity relative to the weed-free control (Table 3.7).

Weed interference reduced white bean yield 59% in this study (Table 3.7). Due to incomplete weed control with pendimethalin, dimethenamid-*P*, S-metolachlor or halosulfuron when applied on their own, there was a decrease in white bean yield of 66, 72, 62 and 21%, respectively. The application of pendimethalin, dimethenamid-*P* or S-metolachlor plus halosulfuron resulted in no white bean yield loss relative to the weed-free control (Table 3.7).

3.5 Conclusion

Based on the results of this study, halosulfuron applied PRE at 35 g ai ha⁻¹ is safe to use on white bean for annual broadleaf weed control. It is also safe to apply halosulfuron on white bean in combination with the soil-applied grass herbicides tested in this study; pendimethalin, dimethenamid-*P* or S-metolachlor. Pendimethalin, dimethenamid-*P* or S-metolachlor in combination with halosulfuron provided full season control of common lambsquarters, wild mustard, redroot pigweed, common ragweed, and green foxtail.

These herbicide tankmixes resulted in sufficient weed control to prevent white bean yield loss. The results of this study suggest that halosulfuron in combination with pendimethalin, dimethenamid-*P* or S-metolachlor would be effective options for broad spectrum weed control in white bean.

Table 3.1. White bean injury (visual rating) 1 and 4 weeks after emergence (WAE) with halosulfuron applied alone and in combination with pendimethalin, dimethenamid-*P* and S-metolachlor applied PRE at Exeter (2013-2014) and Ridgetown, ON, Canada (2014).

Herbicide treatment	Rate g ai ha ⁻¹	Injury	
		1 WAE	4 WAE
		%	
Weedy control		0a	0
Weed-free control		0a	0
Pendimethalin	1080	0a	0
Dimethenamid- <i>P</i>	544	3b	1
S-metolachlor	1050	2b	0
Halosulfuron	35	0a	0
Pendimethalin+ halosulfuron	1080+35	0a	0
Dimethenamid- <i>P</i> + halosulfuron	544+35	3b	1
S-metolachlor+ halosulfuron	1050+35	2ab	0
P-value		0.01	0.24

^a Means followed by the same letter within a column are not significantly different at $\alpha=0.05$.

Table 3.2. Percent control (based on visual rating), density, and dry weight of common lambsquarters in white bean treated with halosulfuron applied alone and in combination with pendimethalin, dimethenamid-P and S-metolachlor applied PRE at Exeter (2013-2014) and Ridgetown, ON, Canada (2014).

Herbicide treatment	Rate g ai ha ⁻¹	Control		Density # m ⁻²	Dry weight g m ⁻²
		4 WAE _____ % _____	8WAE		
Weedy control		0e	0d	19.5e	24.0c
Weed-free control		100a	100a	0.0a	0.0a
Pendimethalin	1080	95b	98a	0.7bc	0.3a
Dimethenamid- <i>P</i>	544	52c	30b	3.0d	8.0b
S-metolachlor	1050	17d	9c	4.5d	10.7bc
Halosulfuron	35	98ab	96a	0.8c	0.2a
Pendimethalin+ halosulfuron	1080+35	100ab	100a	0.2abc	0.1a
Dimethenamid- <i>P</i> + halosulfuron	544+35	99ab	99a	0.2ab	0.2a
S-metolachlor+ halosulfuron	1050+35	99ab	98a	0.3abc	0.3a
P-value		<0.001	<0.001	<0.001	<0.001

^a Means followed by the same letter within a column are not significantly different at $\alpha=0.05$.

Table 3.3. Percent control (based on visual ratings), density, and dry weight of wild mustard in white bean with halosulfuron applied alone and in combination with pendimethalin, dimethenamid-P and S-metolachlor applied PRE at Exeter (2013-2014) and Ridgetown, ON, Canada (2014).

Herbicide treatment	Rate g ai ha ⁻¹	Control		Density # m ⁻²	Dry weight g m ⁻²
		4 WAE _____ % _____	8WAE		
Weedy control		0c	0c	6.6b	34.0b
Weed-free control		100a	100a	0.0a	0.0a
Pendimethalin	1080	48b	7c	4.6b	30.6b
Dimethenamid- <i>P</i>	544	57b	39b	2.1b	21.7b
S-metolachlor	1050	50b	35b	2.7b	22.7b
Halosulfuron	35	98a	100a	0.0a	0.0a
Pendimethalin+ halosulfuron	1080+35	100a	100a	0.0a	0.0a
Dimethenamid- <i>P</i> + halosulfuron	544+35	100a	100a	0.0a	0.0a
S-metolachlor+ halosulfuron	1050+35	100a	100a	0.0a	0.0a
P-value		<0.001	<0.001	<0.001	<0.001

^a Means followed by the same letter within a column are not significantly different at $\alpha=0.05$.

Table 3.4. Percent control (based on visual ratings), density, and dry weight of redroot pigweed in white bean with halosulfuron applied alone and in combination with pendimethalin, dimethenamid-P and S-metolachlor applied PRE at Exeter (2013-2014) and Ridgetown, ON, Canada (2014).

Herbicide treatment	Rate g ai ha ⁻¹	Control		Density # m ⁻²	Dry weight g m ⁻²
		4 WAE _____ % _____	8WAE		
Weedy control		0d	0c	7.2c	33.1b
Weed-free control		100a	100a	0.0a	0.0a
Pendimethalin	1080	69b	67b	2.6b	7.6b
Dimethenamid- <i>P</i>	544	100a	100a	0.3a	0.1a
S-metolachlor	1050	99a	100a	0.1a	0.0a
Halosulfuron	35	100a	100a	0.0a	0.0a
Pendimethalin+ halosulfuron	1080+35	100a	100a	0.0a	0.0a
Dimethenamid- <i>P</i> + halosulfuron	544+35	100a	100a	0.0a	0.0a
S-metolachlor+ halosulfuron	1050+35	100a	100a	0.0a	0.0a
P-value		<0.001	<0.001	<0.001	<0.001

^a Means followed by the same letter within a column are not significantly different at $\alpha=0.05$.

Table 3.5.7 Percent control (based on visual ratings), density, and dry weight of common ragweed in white bean with halosulfuron applied alone and in combination with pendimethalin, dimethenamid-P and S-metolachlor applied PRE at Exeter (2013-2014) and Ridgetown, ON, Canada (2014).

Herbicide treatment	Rate g ai ha ⁻¹	Control		Density # m ⁻²	Dry weight g m ⁻²
		4 WAE _____ % _____	8WAE		
Weedy control		0d	0e	9.0d	35.2c
Weed-free control		100a	100a	0.0a	0.0a
Pendimethalin	1080	9c	2e	5.2cd	22.9bc
Dimethenamid- <i>P</i>	544	41b	19c	2.2b	11.1b
S-metolachlor	1050	11c	3d	3.6bc	20.4bc
Halosulfuron	35	96a	96ab	0.4a	0.7a
Pendimethalin+ halosulfuron	1080+35	97a	90b	0.5a	1.1a
Dimethenamid- <i>P</i> + halosulfuron	544+35	99a	97ab	0.1a	0.6a
S-metolachlor+ halosulfuron	1050+35	97a	97ab	0.3a	0.7a
P-value		<0.001	<0.001	<0.001	<0.001

^a Means followed by the same letter within a column are not significantly different at $\alpha=0.05$.

Table 3.6. Percent control (based on visual ratings), density, and dry weight of green foxtail in white bean with halosulfuron applied alone and in combination with pendimethalin, dimethenamid-P and S-metolachlor applied PRE at Exeter (2013-2014) and Ridgetown, ON, Canada (2014).

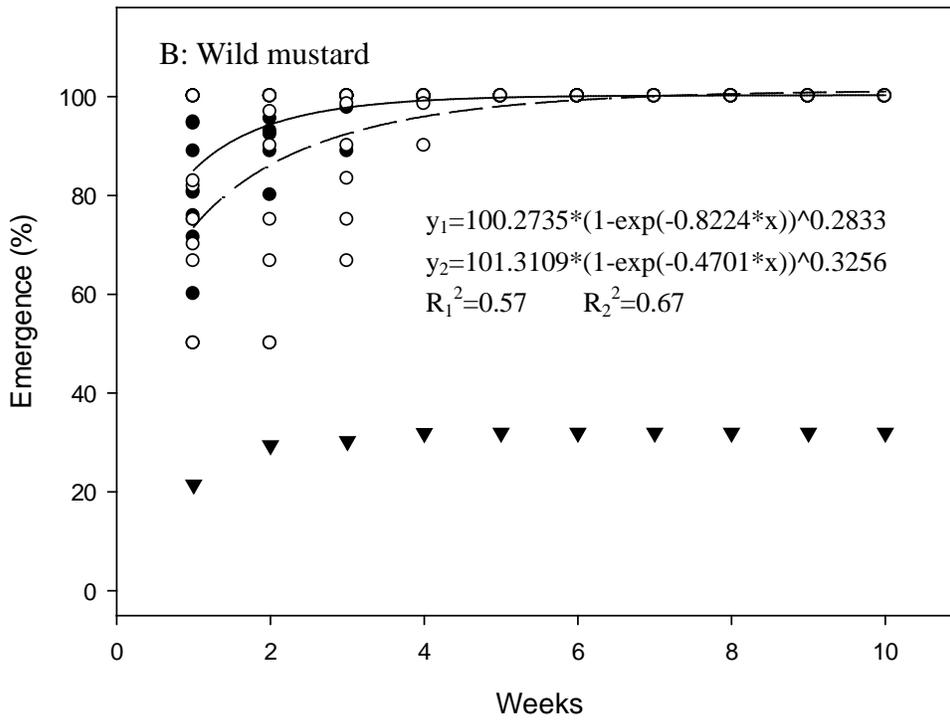
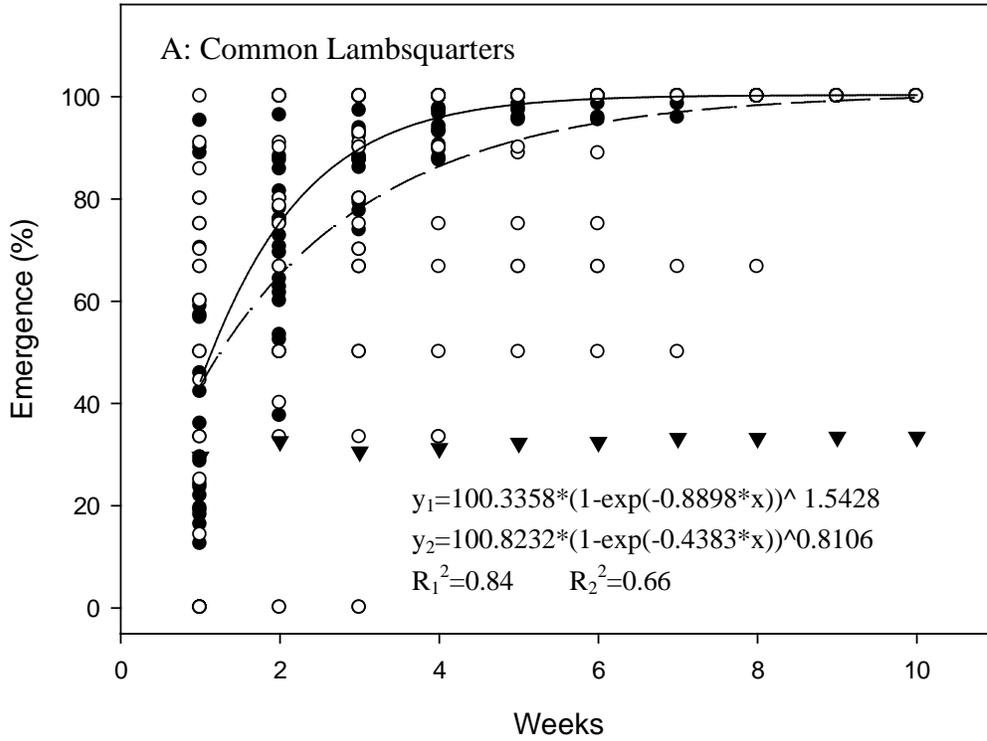
Herbicide treatment	Rate g ai ha ⁻¹	Control		Density # m ⁻²	Dry weight g m ⁻²
		4 WAE _____ % _____	8WAE		
Weedy control		0f	0e	50.9e	84.3f
Weed-free control		100a	100a	0.0a	0.0a
Pendimethalin	1080	92cd	88c	5.5c	5.8d
Dimethenamid- <i>P</i>	544	99ab	92bc	1.5ab	1.0ab
S-metolachlor	1050	99ab	93bc	2.0ab	1.7abc
Halosulfuron	35	53e	44d	25.9d	23.8e
Pendimethalin+ halosulfuron	1080+35	90d	89bc	4.8c	3.8cd
Dimethenamid- <i>P</i> + halosulfuron	544+35	98b	94b	2.3ab	1.6abc
S-metolachlor+ halosulfuron	1050+35	97bc	92bc	3.1bc	2.8bcd
P-value		<0.001	<0.001	<0.001	<0.001

^a Means followed by the same letter within a column are not significantly different at $\alpha=0.05$.

Table 3.7. White bean seed moisture content and yield after treatments with halosulfuron applied alone and in combination with pendimethalin, dimethenamid-P and S-metolachlor applied PRE at Exeter (2013-2014) and Ridgetown, ON, Canada (2014).

Herbicide treatment	Rate	Moisture	Yield
	g ai ha ⁻¹	%	t ha ⁻¹
Weedy control		20.7c	1.2d
Weed-free control		19.0a	2.9a
Pendimethalin	1080	20.4c	1.9c
Dimethenamid- <i>P</i>	544	20.2c	2.1bc
S-metolachlor	1050	20.4c	1.8c
Halosulfuron	35	19.6b	2.3b
Pendimethalin+ halosulfuron	1080+35	19.2ab	2.7a
Dimethenamid- <i>P</i> + halosulfuron	544+35	19.2ab	2.8a
S-metolachlor+ halosulfuron	1050+35	19.3ab	2.7a
P-value		<0.001	<0.001

^a Means followed by the same letter within a column are not significantly different at $\alpha=0.05$.



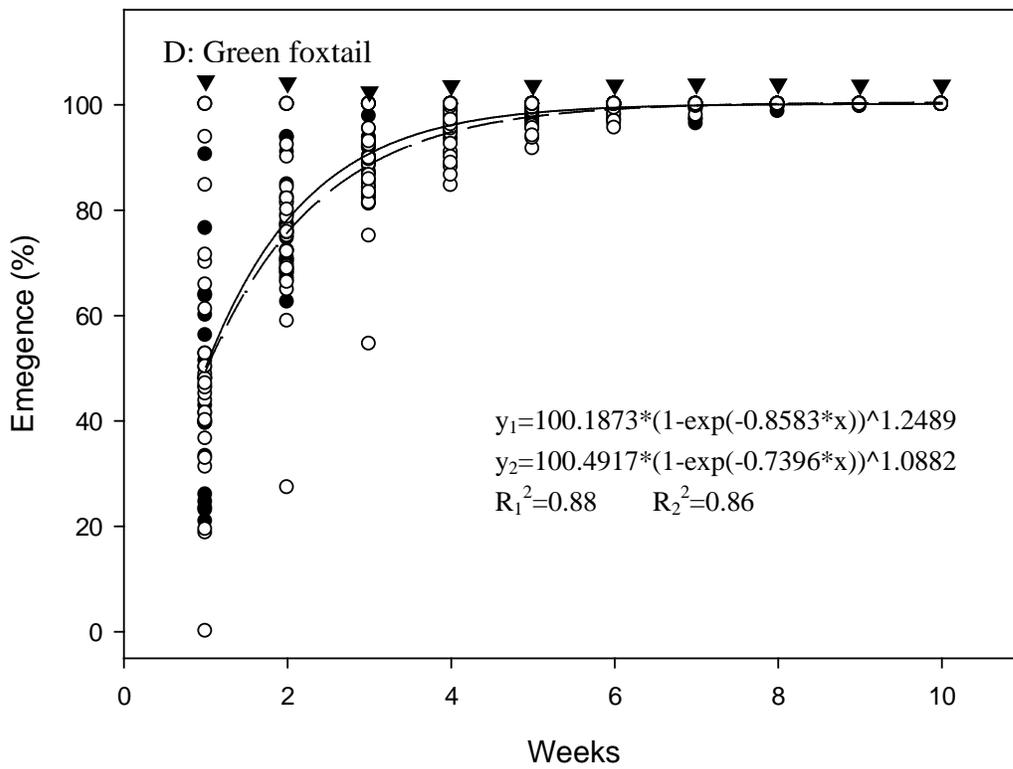
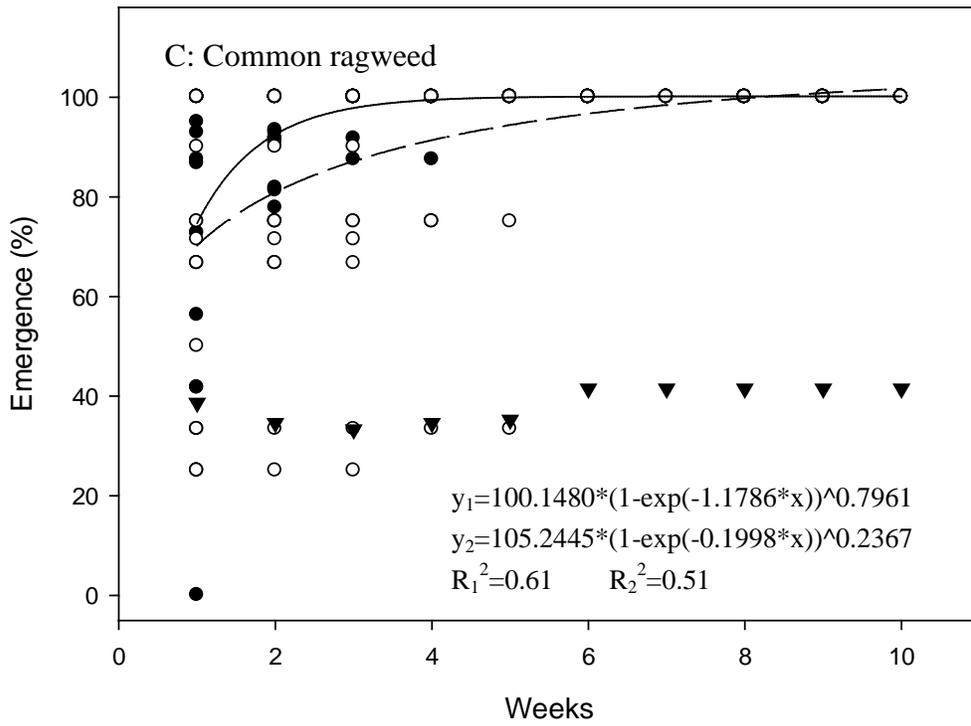


Figure 3.1. Emergence periodicity of annual weed species in white bean with and without influence of halosulfuron. (\bullet , —) and y_1 represents the percent emergence of weeds in weedy control based on final accumulative weeds in weedy control; (\circ , — —) and y_2 represents the percent emergence of weeds in halosulfuron treatment based on final accumulative weeds in halosulfuron treatment; (\blacktriangledown) represents the percent emergence of weeds in halosulfuron based on final accumulative weeds in weedy control.

Chapter 4: Halosulfuron Absorption, Translocation, and Metabolism in White and Adzuki Bean

4.1 Abstract

Halosulfuron, a sulfonylurea herbicide, was registered in late 2014 in Ontario for broadleaf weed control in dry beans. This herbicide has an adequate margin of crop safety in white bean (*Phaseolus vulgaris*) but causes unacceptable injury in adzuki bean (*Vigna angularis*). Halosulfuron-methyl absorption, translocation, and metabolism were evaluated in white and adzuki bean. Adzuki bean had more rapid absorption than white bean, as the time to reach 90% absorption (t_{90}) in adzuki bean was 26 h, significantly faster than white bean (40h). The maximum halosulfuron absorption (A_{\max}) was significantly higher in adzuki bean (76%) than in white bean (65%). In adzuki bean, more ^{14}C -halosulfuron was translocated to the apex, 1st trifoliolate, stem above the treated leaf and roots compared to the white bean. The maximum radioactivity translocated out of the treated leaf (T_{\max}) was significantly higher in adzuki bean (18%) than in white bean (12%). Halosulfuron was broken down to the same metabolites in white and adzuki bean. The half-life of halosulfuron in adzuki bean was 16 HAT, compared to ≤ 6 HAT in white bean. More herbicide remained as the free acid in adzuki bean compared to white bean over the entire 48 h time course. The differential tolerance of white and adzuki bean to halosulfuron can be attributed to greater absorption and translocation and decreased metabolism in adzuki bean.

4.2 Introduction

White (*Phaseolus vulgaris*) and adzuki (*Vigna angularis*) bean are two different dry bean species grown in Ontario. Based on seeded area and total production, white bean has been the most widely grown market class of dry bean in Ontario over the past decade (Statistics Canada 2015). Weed interference can result in substantial yield losses in dry bean (Wilson et al. 1980; Blackshaw and Esau 1991; Chikoye et al. 1995; Chikoye et al. 1996) and herbicides are one of the most common weed management strategies used in dry bean production. When this study was initiated, imazethapyr was the only soil-applied dry bean herbicide for broadleaf weed control in Ontario. Although imazethapyr is very effective for broadleaf weed control in dry beans, one concern is its narrow margin of crop safety under some environmental conditions (Wilson and Miller 1991; Renner and Powell 1992; Arnold et al. 1993; Bauer et al. 1995; Blackshaw and Saindon 1996; Soltani et al. 2007). Halosulfuron was registered in Ontario for weed control in white bean production in 2014. Halosulfuron-methyl (methyl 3-chloro-5-[[[(4,6-dimethoxy-2-pyrimidinyl)amino] carbamoyl]amino]sulfonyl]-1-methyl-1*H*-pyrasole-4-carboxylate) is a sulfonylurea herbicide that provides broad spectrum broadleaf weed control (Brown and Masiunas 2002; Senseman 2007; Soltani et al. 2013d; Soltani et al. 2014a, 2014b). In studies conducted in Ontario, there is adequate margin of crop safety in white bean when halosulfuron is applied PPI, PRE and POST (Soltani et al. 2009; Soltani et al. 2012a), but adzuki bean can be seriously damaged by halosulfuron (Stewart et al. 2010; Soltani et al.

2012a). Halosulfuron applied POST at 35 g ai ha⁻¹ caused 51, 72, and 73% injury in adzuki bean 1, 2, and 4 weeks after application (WAA), respectively and reduced adzuki bean yield 58% (Soltani et al. 2012a).

In most cases, the differential physiological selectivity of acetolactate synthase (ALS) inhibiting herbicides is due to differential absorption, translocation, and/or metabolism (Dubelman et al. 1997; Ma et al. 1997; Gallaher et al. 1999; McElroy et al. 2004; Bukun et al. 2012). Dubelman et al. (1997) reported that corn and wheat metabolized ¹⁴C-halosulfuron-methyl more rapidly than soybean (*Glycine max*). The reason that broadleaf signalgrass (*Brachiaria platyphylla*) is susceptible to nicosulfuron but tolerant to primisulfuron is due to greater absorption and translocation of nicosulfuron (Gallaher et al. 1999). Ma et al. (1997) found less translocation and more rapid metabolism of prosulfuron in sicklepod (*Senna obtusifolia*) than common cocklebur (*Xanthium strumarium*) and common lambsquarters (*Chenopodium album*), which explains why sicklepod is more tolerant to prosulfuron. The reason for higher injury in adzuki bean from halosulfuron-methyl relative to white bean is unknown. Therefore, the objective of this study was to compare halosulfuron-methyl absorption, translocation and metabolism in white and adzuki bean.

4.3 Materials and Methods

Plant Material. 'T9905' white bean (Thompsons Limited, Hensall, ON) and 'Erimo'

adzuki bean (Hensall District Co-op, Hensall, ON) were seeded in 10 cm diameter pots filled with SUNSHINE professional growing mix LA4 (Sungro Horticulture, Agawam, MA). After seeding, all pots were placed in a growth chamber at the University of Guelph with 25/20 C day/night temperature, 16/8 h day/night length and approximately 500 $\mu\text{mol m}^{-2} \text{ s}^{-1}$ light intensity for the absorption and translocation experiments. Adzuki bean was seeded 3 days earlier than white bean, since it emerges more slowly than white bean based on previous experience.

Absorption and Translocation. Uniform white and adzuki bean individuals at the first trifoliolate leaf stage were selected for the study. One unifoliolate leaf of each plant was marked and covered with aluminum foil prior to spraying the beans with commercially formulated halosulfuron-methyl (Permit, Gowan Canada) at 35 g ai ha⁻¹ with 0.25% v v⁻¹ nonionic surfactant (Agral 90, Syngenta Canada Inc., Guelph, ON). Herbicide was sprayed using a single nozzle sprayer with Teejet 8002E nozzle in a spray chamber calibrated to deliver 206 L ha⁻¹ at 275 kPa. The spray was set up 40 cm above the spray bench. After application, the aluminum foil was removed and the protected leaf was treated with a ¹⁴C-labeled halosulfuron-methyl solution which contained commercially formulated halosulfuron, 0.25% v v⁻¹ nonionic surfactant Agral 90, and 0.1 $\mu\text{Ci } ^{14}\text{C}$ halosulfuron-methyl. Ten 1 μl drops of the ¹⁴C treatment solution were applied per leaf. The concentration of the application solution was equivalent to 35 g ai ha⁻¹ halosulfuron-methyl. After application, all plants were returned to the growth chamber

until harvest.

Plants were removed from the soil 6, 12, 24, and 48 h after treatment (HAT) and divided into the following seven parts: treated leaf, root, stem below treated leaf, opposite unifoliate leaf, stem above treated leaf, 1st trifoliate leaf, and plant apex. The treated leaf was washed twice with 10 ml of 9:1:0.05 distilled water, ethanol and Tween 20 mix. Ten ml of Ecolite (ICN Biomedicals Inc., Irvine, CA) was added to scintillation vials and the ¹⁴C halosulfuron-methyl in the leaf wash solution was quantified by liquid scintillation spectrometry (LSS) (Packard Tri-Carb, Model 2500 TR, Packard Instrument Co., Meriden, CT). All plant parts were dried in a 60 C oven for 3 days, weighed, and combusted using a biological sample oxidizer (OX500, R.J. Harvey Instrument Co., Tappan, NY). Radioactivity was quantified by LSS.

Metabolism. All plants were grown as described for the absorption and translocation experiments. Plants were grown in 22/20 day/night temperature greenhouse at Colorado State University, Fort Collins, CO. Under degassed water, sixteen unifoliate leaves of white and adzuki bean were cut at petiole base and transferred to a 0.5 ml microcentrifuge tube. Approximately 0.05 µCi ¹⁴C-halosulfuron-methyl was placed into each microcentrifuge tube. The amount of water that the leaf absorbed was monitored every hour and degassed water was added into the microcentrifuge tube when the water level became low. Water was added to each microcentrifuge tube multiple times to ensure enough ¹⁴C-halosulfuron-methyl would be absorbed by each leaf. Leaves were then

transferred into 6-well Corning Costar cell culture plates (Sigma-aldrich, St. Lois, MO) which contained enough degassed water to ensure leaf survival for the duration of the experiment. Leaves were harvested 6, 12, 24, and 48 HAT. Upon harvest, liquid nitrogen was immediately applied to every leaf to stop metabolism. All samples were dried in a 60 C drier for three days and then ground in 50 ml glass tubes for 3 min with a pestle. Five ml of a solution containing 40% acetonitrile and 60% water was added to ground samples, and vortexed in a RapidVap for 45 min (Labconco, Kansas City, MO). Once the biomass settled, the supernatant was poured off into a separate 50 ml glass tube. This step was repeated two more times until there was a total of at least 15 ml of supernatant. Fifteen ml of the supernatant was then filtered through a 0.45 μm syringe filter using a 20 ml glass syringe. The filtrate was evaporated and centrifuged to dryness using a RapidVap at 38 C under vacuum for 5 h. Samples were re-suspended in 225 μl Mobile Phase A, which contained 89.95% water, 10% acetonitrile, and 0.05% phosphoric acid. Radioactivity levels were determined using reverse-phase high performance liquid chromatography (HPLC; Hitachi Instruments, Inc., San Jose, CA) using a C18 4.6 mm by 250 mm column (Zorbax, Agilent Technologies, Santa Clara, CA, USA). The injection volume was 200 μl . Halosulfuron-methyl was detected at 18.67 ± 0.08 min and halosulfuron free acid was detected at 12.37 ± 0.08 min using the following gradient: 89.95% water: 10% acetonitrile: 0.05% phosphoric acid solution (Mobile Phase A) to 99.95% acetonitrile: 0.05% phosphoric acid solution (Mobile Phase B) over 25 min with a flow rate of 1 ml min^{-1} . Radioactivity was detected using HPLC coupled with an inline radioactivity detector

equipped with a solid cell (Berthold LB 513 radioactivity detector, flow cell YG 400-S5D).

Data Analysis. Experiments were conducted as a randomized complete block design with four replications. The absorption experiment was repeated three more times while the translocation and metabolism experiments were replicated twice. Absorption and translocation out of treated leaf regression was analyzed in R (R Core Team 2015) based on Kniss et al. (2011). Translocation in leaf parts and metabolism regression were plotted using Sigmaplot v. 12.1 (Systat Software Inc., Chicago, USA).

4.4 Results and Discussion

4.4.1 Absorption

Data from the absorption experiments were pooled. The average recovery of applied ^{14}C -halosulfuron was 83 and 82% for white and adzuki bean, respectively. Asymptotic regression and rectangular hyperbolic models were compared using the Akaike Information Criterion (AIC) to determine which function best described absorption data (Kniss et al. 2011). The rectangular hyperbolic model (AIC: 988) (see equation 1 below) provided a better fit compared to the asymptotic regression (AIC: 998), so the rectangular hyperbolic model was used to describe ^{14}C -halosulfuron absorption by white and adzuki bean (Figure 4.1). White bean absorbed 40, 46, 52 and 62% of

applied ^{14}C -halosulfuron, which was significantly less than adzuki which absorbed 52, 60, 65 and 73% at 6, 12, 24, and 48 HAT, respectively ($P=0.0194$; $P=0.0013$; $P=0.0008$; $P=0.0012$). Adzuki bean absorbed more halosulfuron than white bean over the 48 h time period (Figure 4.1). Using the rectangular hyperbolic model shown in Equation 1 (Kniss et al. 2011), the predicted total absorption (A_{max}) was significantly lower ($P<0.001$) in white ($A_{\text{max}} =65.3\%$) compared to adzuki bean ($A_{\text{max}} =75.7\%$) (Figure 4.1). The time required to reach 90% of maximum absorption (t_{90}) was also significantly different. Adzuki bean reach t_{90} in 26 h compared to 40 h for white bean.

$$y = (A_{\text{max}} \times t) / (0.11 \times t_{90} + t) \quad [1]$$

^{14}C -Halosulfuron absorption by white and adzuki bean was similar to the absorption in *Kyllinga* spp. Approximately 48% of applied ^{14}C halosulfuron was absorbed by *Kyllinga* spp. 4 HAT and absorption reached 63% at 96 HAT (McElroy et al. 2004). It was also similar to the absorption rates seen for other ALS inhibiting Group 2 herbicides, where most of the herbicide was absorbed within 24 hours. Imazamox, an ALS inhibiting Group 2 herbicide, was absorbed to a level of 45 and 57% at 6 and 12 HAT, respectively and reached 60% at 96 HAT in Othello pinto bean (*Phaseolus vulgaris* L.) (Bukun et al. 2012). Nicosulfuron, another ALS inhibiting Group 2 herbicide, was absorbed to levels of 40, 57, and 65% by annual bluegrass (*Poa annua* L.) and four other turfgrass at 4, 24, and 96 HAT, respectively (Sidhu et al. 2014). In corn and signalgrass, Gallaher et al. (1999) found that most of the applied primisulfuron and nicosulfuron was absorbed within 24 HAT. Similarly, Frazier et al. (1993) found that primisulfuron absorption in corn reached

76% at 24 HAT with little additional absorption at 48 and 96 HAT (Frazier et al. 1993).

4.4.2 Translocation

Data of two runs of the translocation experiments were combined, since they were not significantly different. Total translocation from the treated leaf to plant tissues above the treated leaf and roots for white and adzuki bean were described by equations 2 and 3.

$$y_w = b + ax \quad [2]$$

$$y_a = a(1 - e^{-bx})^c \quad [3]$$

Equation 2 is a simple linear regression where y_w is halosulfuron translocation in white bean, a is slope, b is the y intercept, and x is time after application, while Equation 3 is an asymptotic regression where y_a is halosulfuron translocation in adzuki bean, a is the maximum translocation, b is slope, c is exponent, and x is time after application.

Radioactivity that remained in the treated leaf of white and adzuki bean 48 HAT was 91 and 82%, respectively. Radioactivity recovered from the treated leaf was not significantly different with 12 and 17%, 25 and 36% in white and adzuki bean at 6 and 48 HAT, respectively. Adzuki bean had significantly higher radioactivity in the treated leaf than white bean at 12 and 24 HAT (Figure 4.2A). Previous studies also found that most of applied ^{14}C -sulfonylurea herbicide remained in the treated leaf. Lycan and Hart (1999) reported that 71-92% of absorbed ^{14}C -thifensulfuron remained in the treated leaf of soybean, velvetleaf and common lambsquarters.

The apex and 1st trifoliate leaf were the plant tissues above the treated leaf. More radioactivity was translocated to the apex and the 1st trifoliate leaf in adzuki bean than in white bean (Figure 4.2B). There was 300, 820, 660 and 160% more radioactivity in the apex of adzuki bean than in white bean at 6, 12, 24 and 48 HAT, respectively. Similarly, there was 575, 1070, 752 and 273% more radioactivity in the 1st trifoliate leaf of adzuki bean than in white bean at 6, 12, 24 and 48 HAT, respectively (Table 4.1). The radioactivity translocated to root was equivalent in white and adzuki bean at 6 HAT. However, at 12, 24 and 48 HAT there was 450, 438 and 208% more radioactivity translocated to the root in adzuki bean than in white bean, respectively (Figure 4.2C). Adzuki bean translocated more radioactivity than white bean over the 48 h time period (Figure 4.2D). The rectangular hyperbolic model (AIC:288) and the asymptotic regression (AIC: 290) provided a similar fit for translocation data. The rectangular hyperbolic model was chosen to describe ¹⁴C-radioactivity translocated out of the treated leaf in white and adzuki bean (Figure 4.2D). Using the rectangular hyperbolic model shown in Equation 1 and redefining A_{\max} as T_{\max} (predicted total translocation) (Kniss et al. 2011), T_{\max} out of the treated leaf was significantly lower ($P < 0.0001$) in white bean ($T_{\max} = 12\%$) compared to adzuki bean ($T_{\max} = 18\%$) (Figure 4.2D). Adzuki bean translocated 90% (t_{90}) of total absorbed radioactivity in 91.1h, more rapidly than white bean ($t_{90} = 199\text{h}$).

Lycan and Hart (1999) reported that thifensulfuron was translocated above the treated leaf more than below the treated leaf (to the roots) in velvetleaf and common

lambsquarters. Frazier et al. (1993) reported that 97% of applied ^{14}C -primisulfuron remained in the treated leaf and less than 1% of absorbed primisulfuron translocated to the shoot and roots. Bukun et al. (2012) reported that only 0.16% of total ^{14}C -imazamox absorbed was translocated out of treated leaves in pinto bean and only 0.1% of total translocated ^{14}C -imazamox was translocated to shoots and roots.

4.4.3 Metabolism

White and adzuki bean produced very similar metabolite profiles (Figure 4.3). The metabolites' retention time in white (9.86 ± 0.07 min) (Figure 4.3B) and adzuki (9.94 ± 0.06 min) (Figure 4.3C) bean were not significantly different. Halosulfuron metabolism in adzuki and white bean was described by the logistic function (equation 2 and 4, respectively).

$$Y = ae^{(-bx)} \quad [4]$$

where y is halosulfuron remaining (peak 4 in figure 4.3), a is the slope of the line, b is the point of inflection, and x is time after application. Halosulfuron free acid metabolism (peak 2 in figure 4.3) was described by equation 3 and metabolite (peak 1 in figure 4.3) in adzuki and white bean was described by equation 2 and 3, respectively.

Halosulfuron was more rapidly metabolized in white than in adzuki bean at 6, 12, 24, and 48 HAT ($P < 0.0001$) (Figure 4.4A). Around 47% of halosulfuron was metabolized by white bean at 6 HAT, reaching 77% at 12 HAT. In contrast, in adzuki bean only 9% of the

halosulfuron was metabolized at 6 HAT, reaching 12% at 12 HAT. Up to 36% of halosulfuron was metabolized by adzuki bean at 48 HAT, which was much lower than the 77% metabolism in white bean at 48 HAT ($P < 0.0001$). The majority of the halosulfuron metabolism in white bean occurred in the first 12 HAT (77.25%) with minimal further metabolism at 12, 24 and 48 HAT (Figure 4.4A). Also, a consistently higher level of halosulfuron free acid remained in adzuki bean than white bean over 48 h (Figure 4.4B). Adzuki bean metabolism resulted in a halosulfuron-methyl half-life of 16 h, compared to a half-life in white bean of less than 6 h (Figure 4.4A). A consistently higher level of halosulfuron free acid (approx. 10% more) remained in adzuki bean compared to white bean over 48 h (Figure 4.4B). Time required to obtain metabolites in adzuki bean was much slower in adzuki bean compared to white bean. Almost all the metabolites occurred in 12 HAT in white bean (Figure 4.4B). All of the results presented explain the reason that adzuki bean is more susceptible to halosulfuron than white bean.

To our knowledge, there have been no previous published studies describing halosulfuron-methyl metabolism in white and adzuki bean. However, halosulfuron-methyl metabolism has been studied in several other species. In *Kyllinga* spp. and soybean cell culture very little metabolism was reported (Dubelman et al. 1997; McElroy et al. 2004), but in corn and wheat (*Triticum aestivum*) cell cultures halosulfuron-methyl was quickly degraded. In soybean cell culture, approximately 86 to 96% of the halosulfuron-methyl was unchanged 168 HAT, while almost 100% was metabolized by corn and wheat 6 HAT. Around 92% of radioactivity was converted to an

unknown metabolite within 12 hours in white bean, which had similar levels of metabolism compared to corn and wheat (Figure 4.4). However, much lower levels of metabolism occurred in adzuki bean compared to corn and wheat (Figure 4.4). The most common metabolic transformation in plants for most sulfonylurea herbicides is glucose conjugation (Rao 2000). Hydroxylation of the pyrimidine ring followed by a rapid conjugation with glucose is the reason, for example, that corn rapidly inactivates halosulfuron-methyl (Dubelman et al. 1997).

4.5 Conclusion

There appear to be several factors contributing to the differential susceptibility of white and adzuki bean to halosulfuron-methyl. Halosulfuron-methyl was absorbed more rapidly and there was significantly more halosulfuron translocation out of the treated leaf in adzuki bean compared to white bean. Metabolism studies confirmed that the half-life of halosulfuron was shorter in white bean compared to adzuki bean. Greater halosulfuron absorption, increased translocation, and reduced metabolism in adzuki bean versus white bean are the primary factors contributing to increased halosulfuron phytotoxicity on adzuki bean observed under field conditions. Although this work has produced a greater understanding of the mechanism responsible for differential susceptibility to halosulfuron-methyl between white bean and adzuki bean, further studies to identify the secondary halosulfuron metabolites in adzuki and white bean would be useful.

Table 4.1. Distribution of radioactivity at 6, 12, 24 and 48 h after foliar application of ¹⁴C-halosulfuron to white and adzuki bean over two experiments.

		¹⁴ C Distribution						
Hours	Species	Treated leaf	Apex	1 st trifoliolate	Stem (above treated leaf)	Stem (below treated leaf)	Root	Opposite leaf
		—————% of total applied per plant—————						
6h	White	11.91	0.02	0.04	0.03	0.21	0.04	0.01
	Adzuki	16.82	0.08	0.27	0.09	0.76	0.05	0.03
	P-value	0.2098	0.0201	0.0467	0.1030	0.0343	0.0988	0.1331
12h	White	16.50	0.06	0.10	0.03	0.46	0.04	0.05
	Adzuki	26.34	0.55	1.17	0.23	1.09	0.22	0.13
	P-value	0.0153	0.0012	0.0077	0.0034	0.0024	<0.0001	0.0239
24h	White	23.90	0.14	0.21	0.09	0.83	0.08	0.097
	Adzuki	31.59	1.06	1.79	0.21	0.68	0.43	0.31
	P-value	0.0442	0.0034	0.0037	0.0129	0.2193	<0.0001	0.0177
48h	White	35.49	0.60	0.78	0.27	1.26	0.13	0.27
	Adzuki	36.37	1.56	2.91	0.25	0.74	0.40	0.57
	P-value	0.7751	0.0083	0.0002	0.7624	0.0010	<0.0001	0.0218

* Bolded values indicate in which tissues and sample times after application when ¹⁴C-halosulfuron radioactivity was greater in adzuki bean than in white bean.

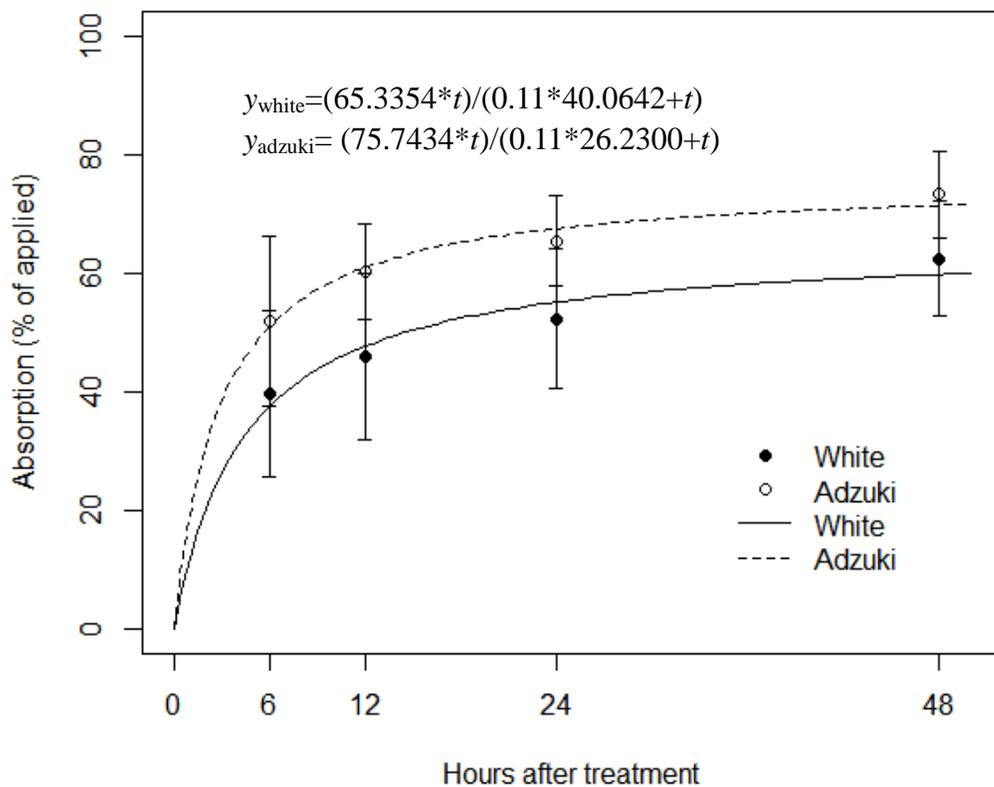
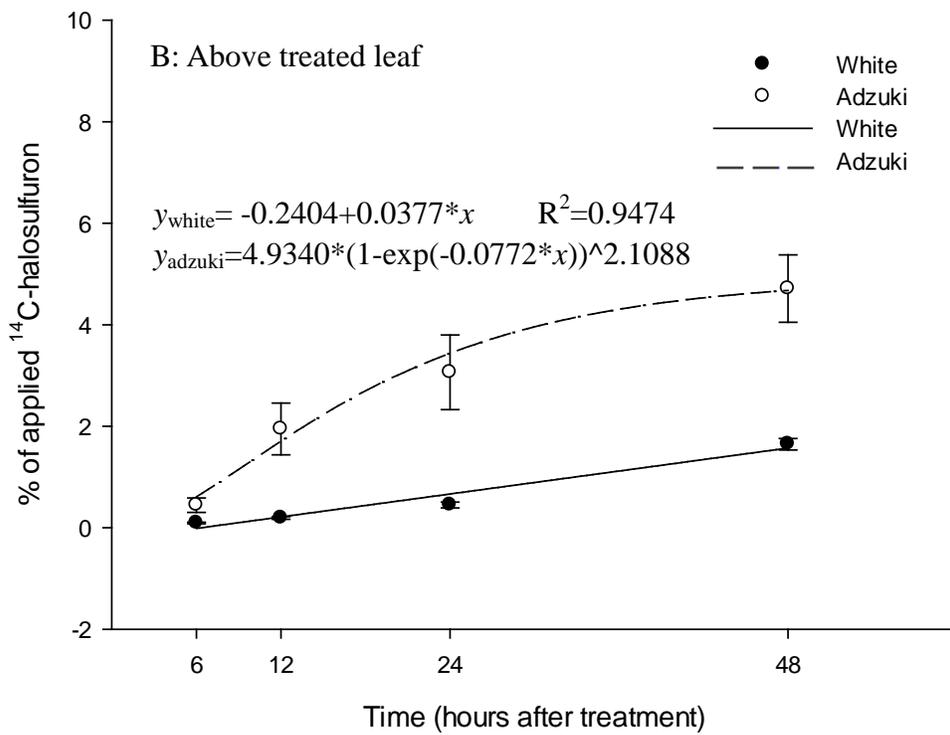
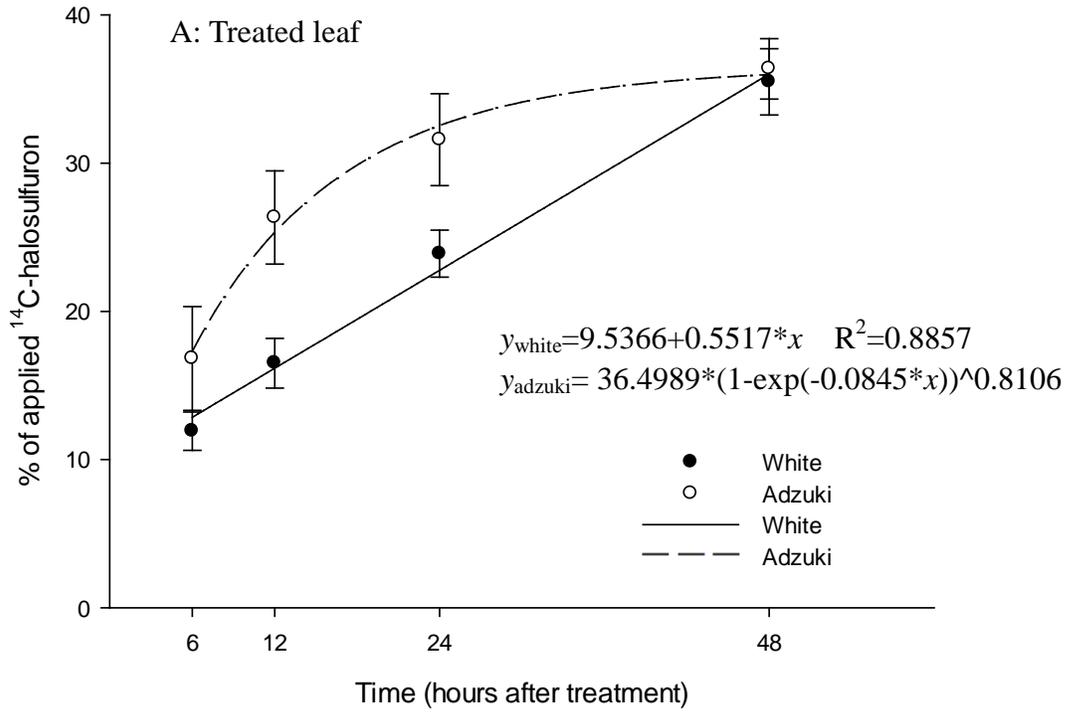
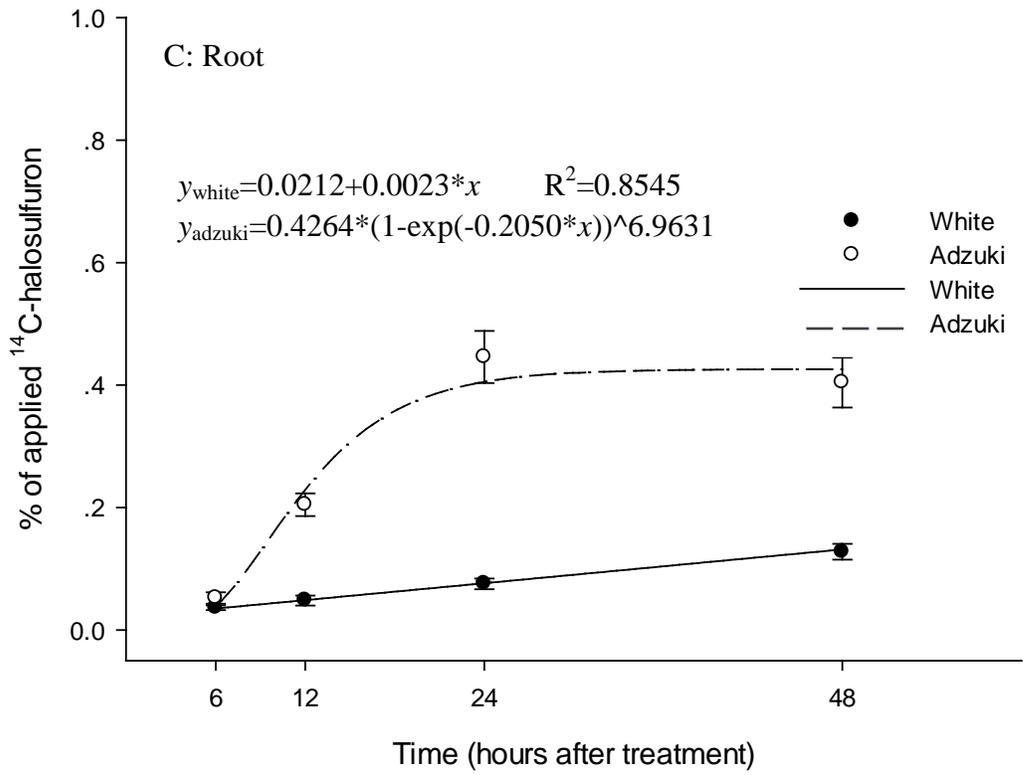


Figure 4.1. Rectangular hyperbolic model for ¹⁴C-halosulfuron absorption, expressed as percent of total applied ¹⁴C-halosulfuron absorbed by white and adzuki bean plants.





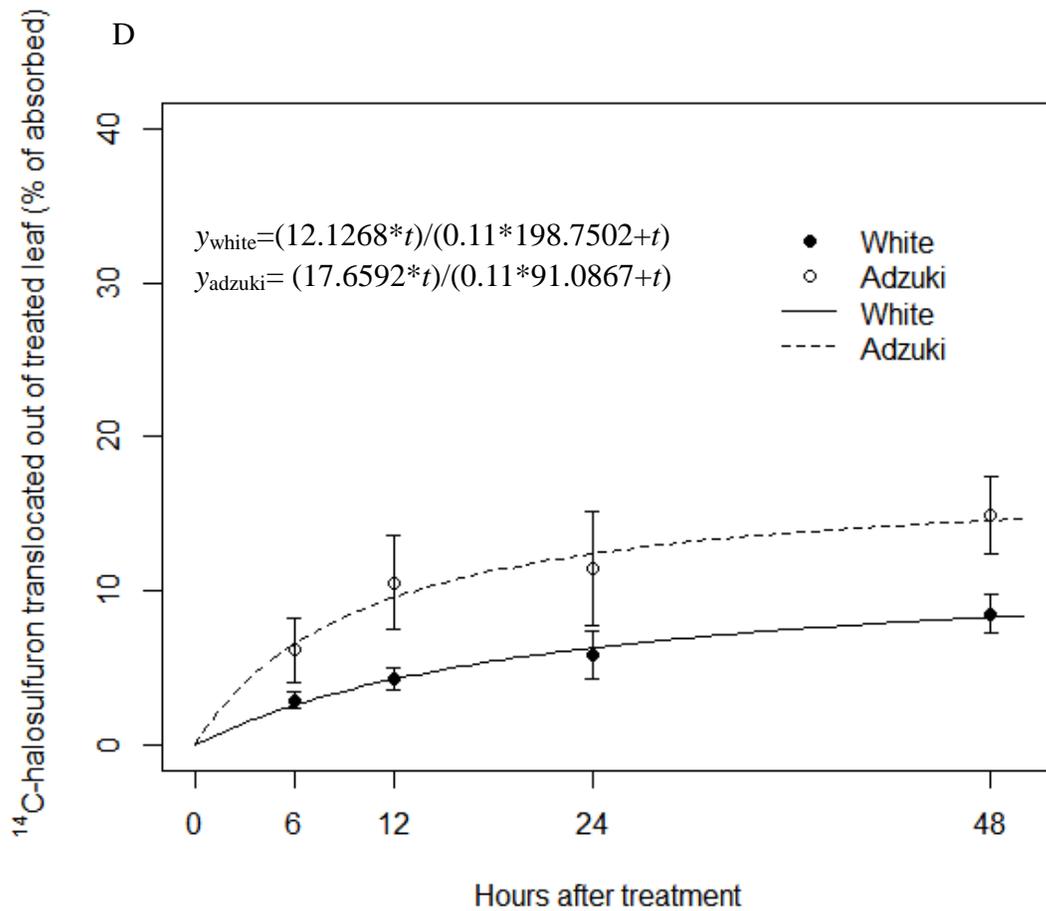


Figure 4.2. Translocation of ^{14}C -radioactivity in white and adzuki bean. A, translocation as percent of total applied radioactivity in treated leaf; B, translocation above treated leaf (1st trifoliolate + apex + stem that above treated leaf) as percent of total applied radioactivity; C, translocation to the root as percent of total applied radioactivity; D, ^{14}C -radioactivity translocated out of the treated leaf (% of total absorbed) in white and adzuki bean.

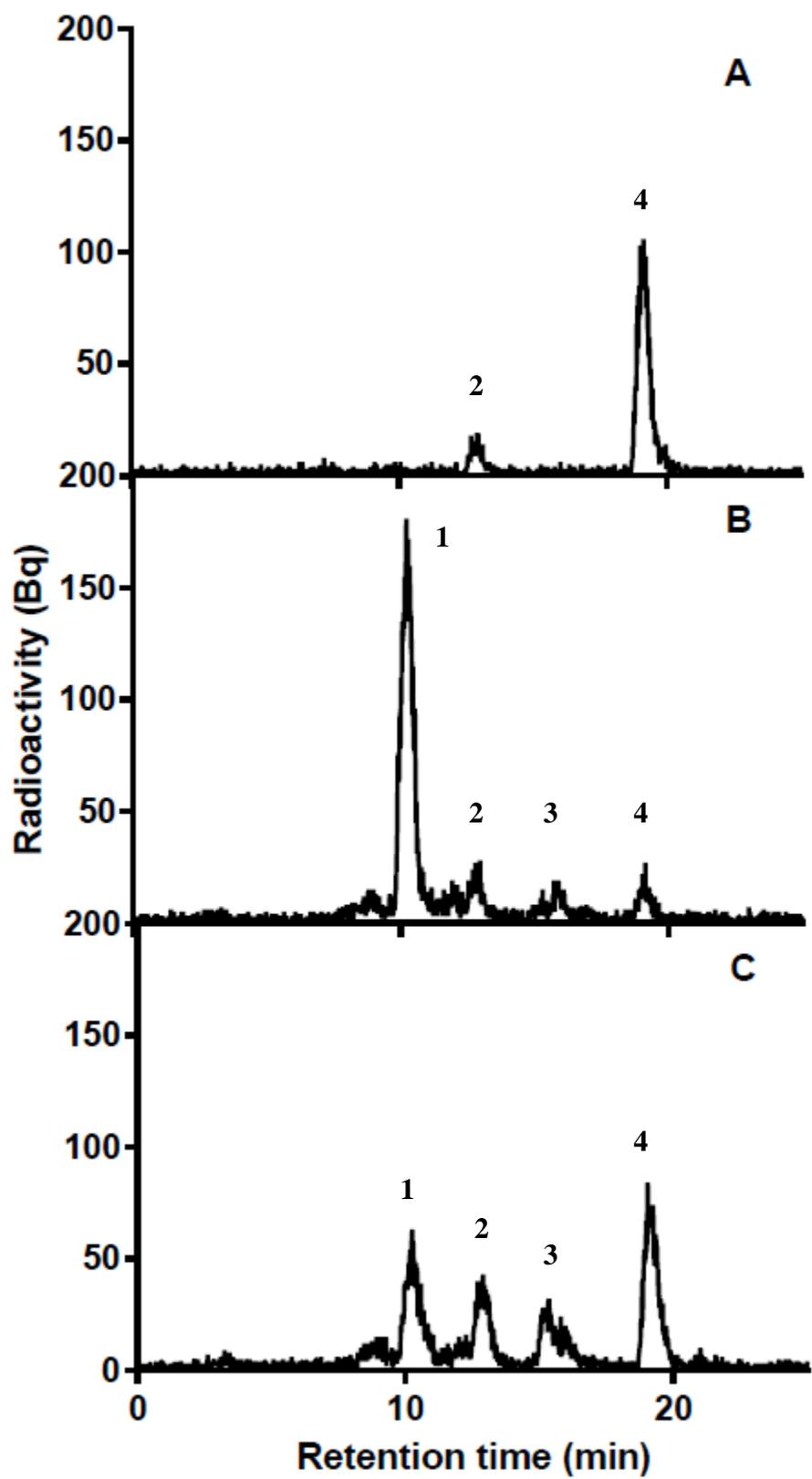
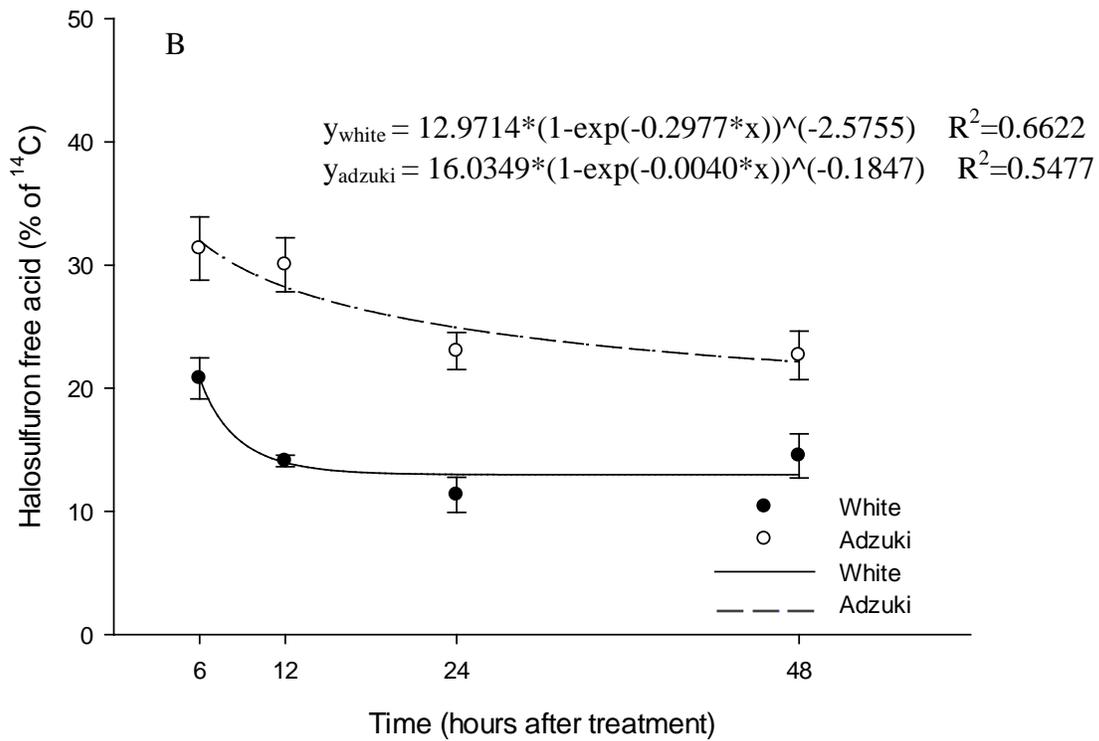
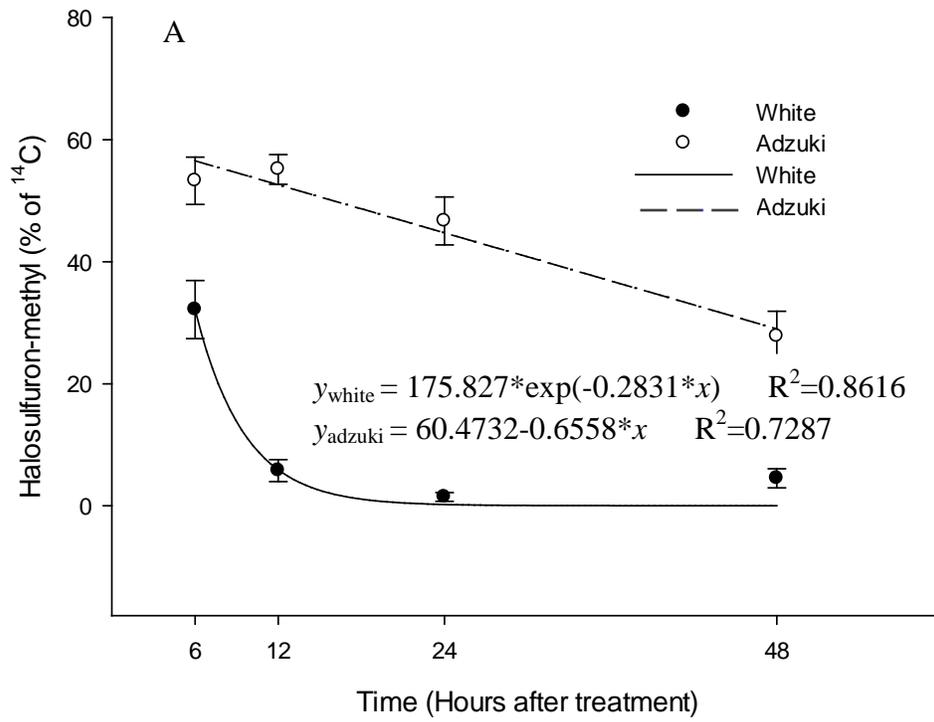


Figure 4.3. HPLC chromatograms of ^{14}C -halosulfuron standard (A), and from excised unifoliate leaf of white (B) and adzuki bean (C) treated with ^{14}C -halosulfuron at 48 HAT. Peaks are labeled as 1) unknown metabolite, 2) halosulfuron free acid, 3) unknown metabolite, and 4) halosulfuron-methyl.



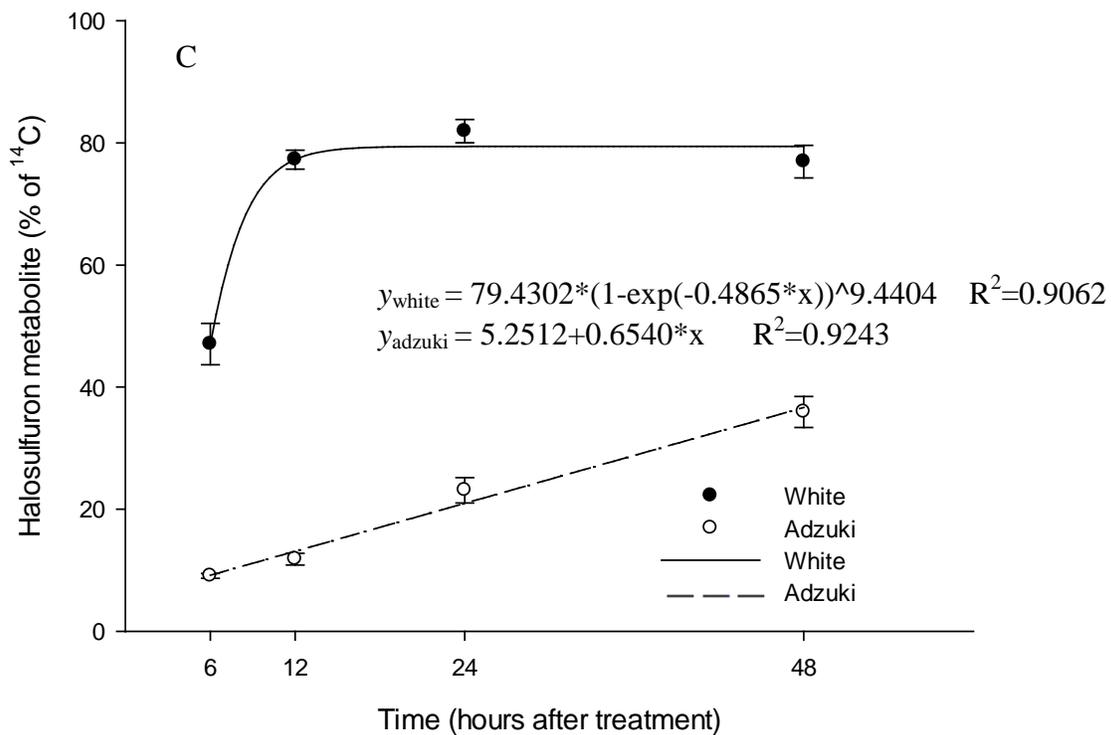


Figure 4.4. Metabolism of ^{14}C -radioactivity in white and adzuki bean during 48 h time course. A: percent of radioactivity as ^{14}C -halosulfuron (Peak 4 in figure 4.3); B: percent of radioactivity as ^{14}C -halosulfuron free acid (Peak 2 in figure 4.3); C: percent of radioactivity as metabolite (Peak 1 in figure 4.3)

Chapter 5: General Discussion

5.1 Contributions

This research evaluated the fit of halosulfuron applied preplant incorporated (PPI) and preemergence (PRE) for broadleaf weed control in dry beans in Ontario. When these study were initiated, Ontario dry bean producers had a limited number of herbicide options for broadleaf weed control, imazethapyr was the only soil-applied herbicide available and fomesafen and bentazon were the only POST herbicides registered in the province. The results clearly demonstrated that halosulfuron, applied PPI or PRE, is an effective herbicide for the control of some broadleaf weeds in dry beans including common lambsquarters, wild mustard, redroot pigweed and common ragweed. In contrast, halosulfuron has very limited activity on annual grasses. Tankmixes of halosulfuron plus trifluralin, pendimethalin, EPTC, dimethenamid-*P* or *S-metolachlor* applied PPI and halosulfuron plus pendimethalin, dimethenamid-*P* or *S-metolachlor* applied PRE provided good to excellent green foxtail control while not compromising broadleaf weed control. The mixture of herbicides which provide annual grass and broadleaf weed control results in labour savings, reduced fuel costs, reduced machinery costs and reduced soil compaction due to a fewer trips across the field. Also, the combination of herbicides from different herbicide groups with different modes of action can reduce selection pressure for herbicide resistant weeds assuming that both herbicides have activity on the same weed species. For example, both halosulfuron and dimethenamid-*P*, applied PPI or

PRE provided greater than 90% control of redroot pigweed, which would be effective in delaying the selection of herbicide resistant redroot pigweed. Overall, the results of this research, and subsequent registration of these tankmixes in Ontario, will provide Ontario dry bean producers with additional herbicide tankmix options for broad spectrum weed control.

This is the first reported research on the absorption, translocation and metabolism of halosulfuron in white compared to adzuki bean. Based on previous studies conducted in Ontario it was known that white bean is tolerant to POST applications of halosulfuron, but adzuki bean is susceptible. However, the basis for this differential response between white and adzuki bean was not known. Based on experiments with ¹⁴C-halosulfuron, this study concludes that the increased sensitivity of adzuki bean relative to white bean to halosulfuron POST is due to increased absorption, increased translocation and reduced metabolism in adzuki bean. These results clearly explain the reasons for the differential sensitivity of adzuki and white bean to halosulfuron applied POST.

5.2 Limitations

The field studies for this project were conducted on only two soil types at the University of Guelph Ridgetown Campus and the Huron Research Station which are not representative of all the soil types that dry beans are grown on in Ontario. The soil organic matter where the field experiments were conducted ranged from 2.9 to 4.7 which

is higher than many fields where dry beans are grown commercially. The relatively high soil organic matter may have resulted in reduced risk of crop injury and weed control due to increased adsorption of the herbicide. The halosulfuron label recommends that the low rate (35 g ai ha⁻¹) which was used in this study, be used on coarse textured soils with low soil organic matter. In addition, the soil pH at the Huron Research Station is relatively high (pH=7.8) (Senseman 2007; Anonymous 2009). Halosulfuron is more water soluble and available for plant uptake at high soil pH which may result in greater crop injury and increased weed control. The results from this study provide a good basis for future research, which should be conducted on coarse textured soils with low soil organic matter and high soil pH to determine if the tankmixes investigated in this study result in less crop tolerance and different weed control levels.

Another limitation of this project was the limited number of weed species included. Only five species had high enough densities and were present at a sufficient number of sites to be included in the analysis. These species were: common lambsquarters, wild mustard, redroot pigweed, common ragweed and green foxtail. Even though the above weed species are some of the most common weeds in Ontario (Frick and Thomas 1992), there are additional weed species that are of concern to Ontario dry bean producers. In future studies, the efficacy of halosulfuron tankmixes should be evaluated on other following annual broadleaf weeds, including, velvetleaf, Eastern black nightshade, wild buckwheat, lady's thumb and annual sowthistle (*Sonchus oleraceus* L.); and on the following annual grass weeds; barnyard grass, crabgrass, witch grass (*Panicum capillare*

L.), fall panicum and proso millet; as well as the following perennial weeds; yellow nutsedge, field bindweed (*Convolvulus arvensis* L.), perennial sowthistle (*Sonchus arvensis* L.) and Canada thistle (*Cirsium arvense* L.) (Peter Sikkema, personal communication, December 2015). The halosulfuron tankmixes evaluated may not control all of the above weed species, thus, farmers need to base their herbicide selection on their own soil characteristics, weed spectrum and future crops in the rotation.

Weather is another key factor influencing weed control efficacy, and weather was a limitation in this project to an extent. In one experiment, dimethenamid-*P* applied alone or in combination with halosulfuron, applied PRE, caused 20 and 40% white bean injury at 1 and 4 weeks after emergence due to heavy rainfall after application. The dimethenamid-*P* label recommends that the herbicide not be applied if heavy rainfall is expected within 48 hours (Senseman 2007). However, rainfall is also required within 10 days to ensure that dimethenamid-*P* is dissolved into soil water solution so that it can be taken up by the developing weed seedlings. In addition, halosulfuron also requires activating soil moisture for optimum PRE weed control (Senseman 2007). Thus, the weather near the time of application influences both the degree of crop injury and weed control efficacy.

Low light intensity in the growth chamber studies used in this project may have been a limitation. For the growth chamber studies, the light level was only $500 \mu\text{mol m}^{-2} \text{s}^{-1}$ which influenced bean growth relative to the field. This was especially true for adzuki bean which grew in a more elongated fashion in the growth chamber compared to the

field. The cuticle on lower leaves of etiolated plants may be thinner than a normal adzuki bean plant which may affect absorption of halosulfuron, since greater absorption may occur with a thinner cuticle (Van Overbeek 1956). However, the response of adzuki bean plants after applying halosulfuron were similar to what we observed under field conditions. Future growth chamber studies should be conducted with higher light intensity.

5.3 Future Research

The halosulfuron label in Canada has a rate range of 25 to 50 g ai ha⁻¹ depending on application method and timing. In this study an intermediate rate of 35 g ai ha⁻¹ was used. Future studies should evaluate a wider range of rates to determine the impact of halosulfuron rate on crop safety and weed control efficacy. Even though the weed pressure in these experiments was high, and the herbicide tankmixes provided good weed control, we did not evaluate either the low or high rate on the current halosulfuron label. It would be useful for Ontario bean producers if they had more information guiding them in terms of scenarios where they may be able to use lower rates or where higher rates may be warranted. Rates of herbicides could be altered according to soil texture and weed pressure, for example the low halosulfuron rate may be appropriate for soils with coarse texture and low organic matter levels (Anonymous 2009). Also, the tolerance of dry bean to the high rate of halosulfuron should be evaluated.

Many Group 2 resistant weeds have been reported in Ontario, including cocklebur, Canada fleabane, green and giant foxtail, common lambsquarters, eastern black nightshade, redroot and green pigweed, common and giant ragweed and waterhemp (Beckie 2014). Future greenhouse studies should be conducted with Group 2 resistant weeds to determine the most efficacious herbicide combinations for control of resistant biotypes. If the greenhouse studies identify efficacious options, further studies could be conducted in the field to verify the results from the greenhouse studies in a "real farming" situation. In addition, future studies should explore integrated weed management systems in dry bean production, such as crop rotation, strip tillage, and the strategic use of tillage and cover crops.

The studies on the metabolism of ^{14}C -halosulfuron in white and adzuki bean should be repeated. The ^{14}C -halosulfuron rates used in the metabolism experiments were much lower than in the absorption experiments. Also, the ^{14}C -halosulfuron was applied POST to the leaf blade while in the field studies halosulfuron was applied PPI and PRE. The objective of the metabolism studies was to determine if there was a different rate of halosulfuron degradation in white and adzuki bean. The uptake of ^{14}C -halosulfuron into the leaf blade achieved the primary objective of the research study, however, if more ^{14}C -halosulfuron had been available it would have been interesting to repeat the metabolism study using different application timings mimicking PPI and PRE applications of halosulfuron, since lower injury has been reported when halosulfuron is applied PPI and PRE in adzuki bean compared to POST (Stewart et al. 2010; Soltani et al.

2015).

Future studies should focus on weed management in adzuki bean since they are more susceptible to many of the herbicides currently registered for weed management in dry beans. Bentazon at 1080 and 2160 g ai ha applied POST to adzuki bean caused 30 and 38% injury at 4 WAA, respectively (Soltani et al. 2006a). However, it could be possible that the addition of bentazon to halosulfuron will reduce crop injury without compromising weed control efficacy. Lycan and Hart (1999) found that combining bentazon with ^{14}C -thifensulfuron decreased the amount of absorption and translocation of ^{14}C out of the treated leaf in velvetleaf and common lambsquarters. Bauer et al. (1995) reported similar results when bentazon was tankmixed with imazethapyr. The absorption of ^{14}C -imazethapyr was decreased by 40% and ^{14}C translocated out of the treated leaf was decreased by 50% when tankmixed with bentazon (Bauer et al. 1995). This study concluded that adzuki bean absorbed more, translocated more, and metabolized less halosulfuron than white bean. If a safener could be developed that would reduce absorption, reduce translocation and increase metabolism of halosulfuron or alteration of halosulfuron metabolites in adzuki bean, halosulfuron would perhaps be a viable herbicide for use in adzuki bean (Abu-Qare and Duncan 2002). In several studies, safeners decreased absorption and/or translocation of herbicides (Ezra and Gressel 1982; Fuerst 1987). Safeners may increase glutathione metabolism by increasing glutathione content in the plants and/or help to induced activity of the glutathione-S-transferase enzyme (Farago et al. 1994; Riechers et al. 1997; Abu-Qare and Duncan 2002).

Chapter 6: Literature Cited

- Abate T. and J. K. O. Ampofo. 1996. Insect pests of beans in Africa: their ecology and management. *Annu. Rev. Entomol.* 41:45-73.
- Abu-Qare A. W. and H. J. Duncan. 2002. Herbicide safeners: uses, limitations, metabolism, and mechanisms of action. *Chemosphere* 48:965-974.
- Agriculture in the classroom. 2010. Beans. Available Online: <http://www.aitc.sk.ca/files/raven/Beans.pdf>. Accessed: May 30, 2013.
- Agricultural Marketing Resource Center. 2011. Dry Edible Bean Profile. Available Online:http://www.agmrc.org/commodities__products/grains__oilseeds/dry-edible-bean-profile. Accessed: May 20, 2013.
- Aleman, F. 2001. Common bean response to tillage intensity and weed control strategies. *Agron. J.* 93:556-563.
- Allmaras, R. R., J. M. Kraft, and D. E. Miller. 1988. Effects of soil compaction and incorporated crop residue on root health. *Annu. Rev. Phytopathol.* 26:219-243.
- Amrhein, J. and H. R. Gerber. 1985. CGA 131'036: a new herbicide for broadleaved weed control in cereals. In 1985 British Crop Protection Conference, Weeds, Vol 1. BCPC Publications, Surrey, pp 55-62. Available Online: http://www.cwss.org/proceedingsfiles/2002/34_2002.pdf. Accessed: December 2, 2013.
- Andersen, R. N., W. E. Lueschen, D. D. Warnes, and W. W. Nelson. 1974. Controlling

broadleaf weeds in soybeans with bentazon in Minnesota. *Weed Sci.* 22:136-142.

Anonymous. 2009. Halosulfuron 75WDG herbicide. Available Online:
http://www.agroconsultasonline.com.ar/ticket.html/2749-528_Halosulfuron_75_WDG_3_29_2010_2_49_02_PM.pdf?op=d&ticket_id=6316&evento_id=12988.

Accessed: Jan 23, 2016.

Arnold, R. N., M. W. Murray, E. J. Gregory, and D. Smeal. 1993. Weed control in pinto beans (*Phaseolus vulgaris*) with imazethapyr combinations. *Weed Technol.* 7:361-364.

Audy, P., C. E. Braat, G. Saindon, H. C. Huang, and A. Laroche. 1996. A rapid and sensitive PCR-based assay for concurrent detection of bacteria causing common and halo blights in bean seed. *Phytopathol.* 86:361-366.

Baber, A. A. and F. W. Marmor. 2002. Sandea: a new herbicide for vegetable crops. California Weed Science Society. Jan 15, 2002.

Ball D. A. 1992. Weed seedbank response to tillage, herbicide, and crop rotation sequence. *Weed Sci.* 40:654-659.

BASF. 2011. Pursuit herbicide. <http://www.cdms.net/ldat/ld01S011.pdf>. Accessed: March 26, 2015.

Bauer, T. A., K. A. Renner, D. Penner, and J. D. Kelly. 1995. Pinto bean (*Phaseolus vulgaris*) varietal tolerance to imazethapyr. *Weed Sci.* 43:417-424.

Baumann, P. A. 2008. Herbicides: how they work and the symptoms they cause. <http://hdl.handle.net/1969.1/86804>. Publication E-529 10/08. AgriLife Extension. Texas

A&M System. Accessed: September 14, 2013.

Beckie H. 2014. Status of herbicide resistant in Canada. International survey of herbicide resistant weeds. Available Online:
<http://weedsociety.org/summary/country.aspx?CountryID=7>. Accessed: Jan 23, 2016.

Betts, M. F. and I. N. Morrison. 1979. Fall and spring applications of trifluralin and metribuzin in Fababeans (*Vicia faba*). *Weed Sci.* 27:691-695.

Bicksler A. and J. B. Masiunas. 2005. Halosulfuron for weed control in snap beans. North Central Weed Science Society Proceeding. 60:193.

Blackshaw, R. E. 1991. Hairy nightshade (*Solanum sarrachoides*) interference in dry beans (*Phaseolus vulgaris*). *Weed Sci.* 39:48-53.

Blackshaw, R. E. and G. Saindon. 1996. Dry bean (*Phaseolus vulgaris*) tolerance to imazethapyr. *Can. J. Plant Sci.* 76:915-919.

Blackshaw, R. E., L. J. Molnar, H. H. Muendel, G. Saindon, and X. Li. 2000. Integration of cropping practices and herbicides improves weed management in dry bean (*Phaseolus vulgaris*). *Weed Technol.* 14:327-336.

Blackshaw, R. E. and R. Esau. 1991. Control of broadleaf weeds in pinto beans (*Phaseolus vulgaris*). *Weed Technol.* 5:532-538.

Blad B. L., J. R. Steadman, and A. Weiss. 1978. Canopy structure and irrigation influence white mold disease and microclimate of dry edible beans. *Phytopathology.* 68:1431-1437.

- Boutsalis, P. 2001. Herbicide Resistance Action Committee (HRAC). Available Online: <http://www.hracglobal.com/>. Accessed: December 2, 2013.
- Boydston, R. A. 2007. Potato and weed response to postemergence-applied halosulfuron, rimsulfuron and EPTC. *Weed Technol.* 21:465-469.
- Brown, D. and J. Masiunas. 2002. Evaluation of herbicides for pumpkin (*Cucurbita* spp.). *Weed Technol.* 16:282-292.
- Brown, H. M. 1990. Mode of action, crop selectivity, and soil relations of the sulfonylurea herbicides. *Pestic. Sci.* 29:263-281.
- Bryson, C. T. 1988. Effects of rainfall on foliar herbicides applied to seedling johnsongrass (*Sorghum halepense*). *Weed Technol.* 2:153-158.
- Buckelew, J. K. 2005. Eastern black nightshade (*Solanum ptycanthum* Dun.) management in plasticulture tomato (*Lycopersicon esculentum*). Available Online: <http://repository.lib.ncsu.edu/ir/bitstream/1840.16/634/1/etd.pdf>. Accessed: December 13, 2013.
- Bullied, W. J., A. M. Marginet, and R. C. Van Acker. 2003. Conventional- and conservation-tillage systems influence emergence periodicity of annual weed species in canola. *Weed Sci.* 51:886-897.
- Buker, R. S., W. M. Stall, and S. M. Olson. 1998. Watermelon tolerance to halosulfuron applied preemergence and postemergence. *Proc. Annu. Meet. Fla. State. Hort. Soc.* 110:323-325.

- Bukun, B., S. J. Nissen, D. L. Shaner, and J. D. Vassios. 2012. Imazamox absorption, translocation, and metabolism in red lentil and dry bean. *Weed Sci.* 60:350–354.
- Chen, Y., C. Cavers, S. Tessier, F. Monero, and D. Lobb. 2005. Short-term tillage effects on soil cone index and plant development in a poorly drained, heavy clay soil. *Soil Till. Res.* 82:161-171.
- Chikoye, D., S. F. Weise, and C. J. Swanton. 1995. Influence of common ragweed (*Ambrosia artemisiifolia*) time of emergence and density on white bean (*Phaseolus vulgaris*). *Weed Sci.* 43:375-380.
- Chikoye, D., L. A. Hunt, and C. J. Swanton. 1996. Simulation of competition for photosynthetically active radiation between common ragweed (*Ambrosia artemisiifolia*) and dry bean (*Phaseolus vulgaris*). *Weed Sci.* 44:545-554.
- Chomas, A. J. and J. J. Kells. 2004. Triazine-resistant common lambsquarters (*Chenopodium album*) control in corn with preemergence herbicides. *Weed Technol.* 18:551-554.
- Crafts, A.S. 1962. Use of labeled compounds in herbicide research. *Int. J. Appl. Radiat. Isot.* 13:407-415.
- Croissant, R. L., H. F. Schwartz, and P. D. Ayers. 1991. Soil compaction and tillage effects on dry bean yields. *J. Prod. Agric.* 4:461-464.
- Dawson, J. H. 1964. Competition between irrigated field beans and annual weeds. *Weeds.* 12:206-208.
- Dermiyati, S. K. and I. Yamamoto. 1997a. Degradation of the herbicide

- halosulfuron-methyl in two soils under different environmental conditions. *J. Pestic. Sci.* 22:282–287.
- Dermiyati, S. K. and I. Yamamoto. 1997b. Relationships between soil properties and sorption behavior of the herbicide halosulfuron-methyl in selected Japanese soils. *J. Pestic. Sci.* 22:288–292.
- Duggleby, R. G., J. A. McCourt, and L. W. Guddat. 2008. Structure and mechanism of inhibition of plant acetohydroxyacid synthase. *Plant Physiol. Biochem.* 46:309-324.
- Earl, H. J., J. A. Ferrell, W. K. Vencill, M. W. van Iersel, and M. A. Czarnota. 2004. Effects of three herbicides on whole-plant carbon fixation and water use by yellow nutsedge (*Cyperus esculentus*). *Weed Sci.* 52:213-216.
- Ezra, G. and J. Gressel. 1982. Rapid effects of thiocarbamate herbicide and its chloroacetamide protectants on macromolecular synthesis and glutathione levels in maize cell culture. *Pestic. Biochem. Physiol.* 17:48-58.
- Fageria, N. K., A. B. Dos Santos, and A. Moreira. 2010. Yield, nutrient uptake, and changes in soil chemical properties as influenced by liming and iron application in common bean in a no-tillage system. *Commun. Soil Sci. Plant Anal.* 41:1740-1749.
- Farago, S., C. Brunold, and K. Kreuz. 1994. Herbicide safeners and glutathione metabolism. *Physiol. Plantarum.* 91:537-542.
- Fay, P. K. and W. A. Olson. 1978. Technique for separating weed seed from soil. *Weed Sci.* 26:530-533.
- Ferrell, J. A., H. J. Earl, and W. K. Vencill. 2004. Duration of yellow nutsedge (*Cyperus*

esculentus) competitiveness after herbicide treatment. *Weed Sci.* 52:24-27.

Ferrell, J. A., T. R. Murphy, L. L. Burpee, and W. K. Vencill. 2003. Effect of brown patch (caused by *Rhizoctonia solani*) control on preemergence herbicide efficacy in tall fescue (*Festuca arundinacea*). *Weed Technol.* 17:747-750.

Frazier, T. L., S. J. Nissen, D. A. Mortensen, and L. J. Meinke. 1993. The influence of terbufos on primisulfuron absorption and fate in corn (*Zea mays*). *Weed Sci.* 41:664-668.

Fredeen, A. L., I. M. Rao, and N. Terry. 1989. Influence of phosphorus nutrition on growth and carbon partitioning in *Glycine max*. *Plant Physiol.* 89:225-230.

Frick B., and A. G. Thomas. 1992. Weed surveys in different tillage systems in southwestern Ontario field crops. *Can. J. Plant Sci.* 72:1337-1347.

Friesen G. H. 1987. Wild mustard (*Sinapis arvensis*) control in sunflowers (*Helianthus annuus*) with flurochloridone. *Weed Sci.* 35:228-230.

Fuerst, E. P. 1987. Understanding the mode of action of chloroacetanilide and thiocarbamate herbicides. *Weed Technol.* 1:270-277.

Gentry H. S. 1969. Origin of the common bean, *Phaseolus vulgaris*. *Econ. Bot.* 23:55-69.

Glover, D. G., and W. T. Schapaugh. Inheritance of resistance to pendimethalin herbicide induced stem damage in soybean. *Euphytica* 125:433-437.

Gray, R. A. 1965. A vapor trapping apparatus for determining the loss of EPTC and other herbicides from soils. *Weeds* 138-141.

Green, D. E., L. E. Cavanah, and E. L. Pinnell. 2005. Effect of seed moisture content,

field weathering, and combine cylinder speed on soybean seed quality. *Crop Sci.* 6:7-10.

Grey, T. L., W. K. Vencill, N. Mantripagada, and A. S. Culpepper. 2007. Residual herbicide dissipation from soil covered with low-density polyethylene mulch or left bare. *Weed Sci.* 55:638-643.

Grichar, W. J., B. A. Besler, and K. D. Brewer. 2003. Purple nutsedge control and potato (*Solanum tuberosum*) tolerance to sulfentrazone and halosulfuron. *Weed Technol.* 17:485-490.

Gunsolus, J. L., and W. S. Curran. 1999. Herbicide mode of action and injury symptoms. North Central Regional Extension Publications. Available Online: <http://pdf.thepdfportal.com/PDFFiles/87592.pdf>. Accessed: May 2, 2014.

Hagedorn, D. J. and D. A. Inglis. 1986. Handbook of Bean Diseases. University of Wisconsin.

Hart, S. E. and D. J. Maxwell. 1995. Postemergence broadleaf weed control in corn. *Weed Sci.* 45:434-438.

Harveson R. M., J. A. Smith, and W. W. Stroup. 2005. Improving root health and yield of dry beans in the Nebraska Panhandle with a new technique for reducing soil compaction. *Plant Dis.* 89:279-284.

Health Canada Pest Management Regulatory Agency (PMRA). 2008a. Bentazon. http://publications.gc.ca/collections/collection_2008/pmra-arla/H113-28-2008-7E.pdf. Accessed: May 12, 2014.

- Health Canada Pest Management Regulatory Agency (PMRA). 2008b. S-ethyl dipropylthiocarbamate (EPTC). Available Online: http://publications.gc.ca/collections/collection_2008/pmra-arla/H113-28-2008-6E.pdf. Accessed: May 9, 2014.
- Health Canada Pest Management Regulatory Agency (PMRA). 2009. Dimethenamid. [http://publications.gc.ca/collections/collection_2009/arla-pmra/H113-29-2009-4E.pdf](http://publications.gc.ca/collections/collection_2009/arla-pmra/H113-29-2009-4E.pdf?f?frbrVersion=6). Accessed: May 9, 2014.
- Health Canada Pest Management Regulatory Agency (PMRA). 2010. Imazethapyr. http://publications.gc.ca/collections/collection_2011/sc-hc/H113-27-2010-2-eng.pdf. Accessed: May 12, 2014.
- Hein G. L. and F. B. Peairs. 2006a. Dry beans XIII-1 seedcorn maggot. Available Online: <http://wiki.bugwood.org/uploads/SeedcornMaggot-DryBeans.pdf>. Accessed: June 20, 2013.
- Hein G. L. and F. B. Peairs. 2006b. Dry beans XIII-5 Mexican bean beetle. Available Online: <http://wiki.bugwood.org/uploads/MexicanBeanBeetle-DryBeans.pdf>. Accessed: June 20, 2013.
- Hekmat, S., N. Soltani, C. Shropshire, and P. H. Sikkema. 2008. Effect of imazamox plus bentazon on dry bean (*Phaseolus vulgaris* L.). *Crop Prot.* 27:1491-1494.
- Hensall District Co-operative. 2009. Coloured beans seed. Available Online: www.hdc.on.ca/food/seed/coloured.php. Accessed: May 7, 2013.

- Hutchinson, P. J. 2012. Common lambsquarters and hairy nightshade control in potato with dimethenamid-p alone and in tank mixtures and comparison of control by dimethenamid-p with S-metolachlor and metolachlor. *Weed Technol.* 26:279-283.
- Hutchinson P. J., C. V. Ransom, R. A. boydston, and B. R. Beutler. 2005. Dimethenamid-p: efficacy and potato (*Solanum tuberosum*) variety tolerance. *Weed Technol.* 19:996-971.
- Isaacs, M. A., H. P. Wilson, and J. E. Toler. 2003. Combinations of sethoxydim with postemergence broadleaf herbicides in sethoxydim-resistant corn (*Zea mays*). *Weed Technol.* 17:224-228.
- Issacs, M. A., K. K. Hatzios, H. P. Wilson, and J. Toler. 2006. Halosulfuron and 2,4-D mixtures' effects on common lambsquarters (*Chenopodium album*). *Weed Technol.* 20:137-142.
- Junk, D. C. 2005. Seedcoat darkening in pinto bean (*Phaseolus vulgaris* L.). Doctoral dissertation, University of Saskatchewan, Saskatoon.
- Kniss, A. R., J. D. Vassios, S. J. Nissen, and C. Ritz. 2011. Nonlinear regression analyses of herbicide absorption studies. *Weed Sci.* 59:601-610.
- Knodel J. J., P. B. Beauzay, D. W. Franzen, H. J. Kandel, S. G. Markell, J. M. Osorno, and R. K. Zollinger. 2012. Dry bean grower survey. Available Online: <http://www.ag.ndsu.edu/pubs/plantsci/rowcrops/e1602.pdf>. Accessed: June 15, 2013.
- Koehler, H. H., C. H. Chang, G. Scheier, and D. W. Burke. 1987. Nutrition composition protein quality and sensory properties of thirty-six cultivars of dry beans (*Phaseolus*

vulgaris). J. Food Sci. 52:1335-1340.

Kolasinska, K., J. Szyrmer, and S. Dul. 2000. Relationship between laboratory seed quality tests and field emergence of common bean seed. Crop Sci. 40:470-475.

Kumuduni K. 2014. Estimated Area, Yield, Production and Farm Value of Specified Field Crops, Ontario, 2011-2014. Ontario Ministry of Agriculture and Food and Rural Affairs. Available Online:
http://www.omafra.gov.on.ca/english/stats/crops/estimate_new.htm#metric.

Accessed: Jan 20, 2015.

Liebman, M. and E. Dyck. 1993. Crop rotation and intercropping strategies for weed management. Ecol. Appl. 3:92-122.

Liebman, M., S. Corson, R. J. Rowe, and W. A. Halteman. 1995. Dry bean response to nitrogen fertilizer in two tillage and residue management system. Agronomy J. 87:538-546.

Lindgren D. T. and D. P. Coyne. 1995. Injury and yield of leafhopper-infested dry beans. J. Amer. Soc. Hort. Sci. 120:839-842.

Linscott, D. L. and R. H. Vaughan. 1990. Fenoxaprop for annual foxtail (*Setaria* sp.) control in seedling perennial forages. Weed Technol. 4:560-564.

Long, R., S. Temple, J. Schmierer, M. Canevari, and R. D. Meyer. 2010. Common dry bean production in California. Second edition. 16 p.

- Lycan, D. W. and S. E. Hart. 1999. Physiological response of soybean (*Glycine max*) and two weed species to thifensulfuron and bentazon combinations. *Weed Sci.* 47:143-148.
- Malik, V. S., C. J. Swanton, and T. E. Michaels. 1993. Interaction of white bean (*Phaseolus vulgaris*) cultivars, row spacing, and seeding density with annual weeds. *Weed Sci.* 41:62-68.
- Markell S., M. Wunsch, and L. Rio. 2012. Anthracnose of dry beans. *Plant Dis.* <https://www.ag.ndsu.edu/pubs/plantsci/pests/pp1233.pdf>. Accessed: July 20, 2013.
- McCullough, P. E., Hart, S. E., Brosnan, J. T., and G. K. Breeden. 2011. Aminocyclopyrachlor enhances fenoxaprop efficacy for smooth crabgrass control. *Weed Technol.* 25:506-510.
- McElroy J. S., F. H. Yelverton, I. C. Burke, and J. W. Wilcut. 2004. Absorption, translocation, and metabolism of halosulfuron and trifloxysulfuron in green kyllinga (*Kyllinga brevifolia*) and false-green kyllinga (*K. gracillima*). *Weed Sci.* 52:704-710.
- McGee, B. 2013. Historical Provincial Estimates by Crop, Ontario, 1981-2012. Ontario Ministry of Agriculture, Food and Rural affairs. Available Online: www.omafra.gov.on.ca/english/stats/crops. Accessed: May 7, 2013.
- Morrison, I. N., B. G. Todd, and K. M. Nawolsky. 1989. Confirmation of trifluralin-resistant green foxtail (*Setaria viridis*) in Manitoba. *Weed Technol.* 3:544-551.

- Nelson, K. A. and K. A. Renner. 2002. Yellow nutsedge (*Cyperus esculentus*) control and tuber production with glyphosate and ALS-inhibiting herbicides. *Weed Technol.* 16:512-519.
- Ongley, E. D. 1996. Pesticides as water pollutants. *Control of Water Pollution from Agriculture*. No. 55. Food and Agriculture Org.
- Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA). 2009. *Agronomy Guide for Field Crops*. Publication 811. OMAF, Toronto, ON. Canada, 109 pp.
- Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA). 2012. *Guide to Weed Control*. Publication 75. OMAF, Toronto, ON. Canada, 396 pp.
- Palmer, C., E. Vea, and K. Hester. 2012. IR-4 ornamental horticulture program dimethenamid-p crop safety. Available Online: http://ir4.rutgers.edu/ir4_pdf/default.aspx?pdf=http://ir4.rutgers.edu/Ornamental/SummaryReports/DimethenamidDataSummary2012.pdf. Accessed: September 14, 2013.
- Pan-UK. 2003. Current pesticide spectrum, global use and major concerns. Available Online: <http://www.pan-uk.org/archive/Publications/Briefing/Xroads.pdf>. Accessed: December 15, 2013.
- Peachey, E., D. Doohan, and T. Koch. 2012. Selectivity of fomesafen based systems for preemergence weed control in cucurbit crops. *Crop Protection*. 40:91-97.
- Poling, K. W., K. A. Renner, and D. Penner. 2009. Dry edible bean class and cultivar response to dimethenamid and metolachlor. *Weed Technol.* 23:73-80.

- Powles, S. B., C. Preston, I. B. Bryan, and A. R. Jutsum. 1997. Herbicide resistance: impact and management. *Adv. in Agron.* 58:57-93.
- Radosevich, S. R., S. R. Radosevich, C. Ghersa, and J. S. Holt. 2007. Ecology of weeds and invasive plants: Relationship to agriculture and natural resource management. Pages 385-438 in N. J. Hoboken, ed. *Agricola*. Ipswich, MA: EBSCO.
- Rao V. S. 2000. Principles of weed science. 2nd edition. Science publishers, Inc. United States of America. Pp. 543.
- Relyea R. A. 2005. The impact of insecticides and herbicides on the biodiversity and productivity of aquatic communities. *Ecol Appl* 15:618–627.
- Renner, K. A. and G. E. Powell. 1992. Response of navy bean (*Phaseolus vulgaris*) and wheat (*Triticum aestivum*) grown in rotation to clomazone, imazethapyr, bentazon, and acifluorfen. *Weed Sci.* 40:127-133.
- Retzinger, E. J. and C. Mallory-Smith. 1997. Classification of herbicides by site of action for weed resistance management strategies. *Weed Technol.* 11:384-393.
- Riechers, D. E., G. P. Irzyk, S. S. Jones, and E. P. Fuerst. 1997. Partial characterization of glutathione S-transferases from wheat (*Triticum* spp.) and purification of a safener-induced glutathione S-transferase from *Triticum tauschii*. *Plant Physiol.* 114:1461-1470.
- Robertson, L. S. and R. D. Frazier. 1978. Dry bean production. Cooperative extension service, Michigan State University. 225p.

- Saari, L. L., J. C. Cotterman, and D. C. Thill. 1994. Resistance to acetolactate synthase inhibiting herbicides. Pages 83-139 *in* S. B. Powles and J. A. M. Holtum, eds. *Herbicide Resistance in Plants: Biology and Biochemistry*. Boca Raton, FL: CRC Press.
- Sacks, F. M. 1977. A literature reivew of *Phaseolus angularis*: the adzuki bean. *Econ. Bot.* 31:9-15.
- Schoonhoven A. V. and O. Voysest, eds. 1991. *Common beans research for crop improvement*. Wallingford: CAB. 980 p.
- Scott, R. C., D. R. Shaw, R. L. Ratliff, and L. J. Newsom. 1998. Synergism of grass weed control with postemergence combination of SAN 582 and fluazifop-p, imazethapyr, or sethoxydim. *Weed Technol.* 12:268-274.
- Senseman, S. A. 2007. *Herbicide Handbook*. 9th ed. Champaign, IL. Weed Science society of America. Pp. 76-78.
- Sidhu, S. S., J. Yu, and P. E. McCullough. 2014. Nicosulfuron absorption, translocation, and metabolism in annual bluegrass and four turfgrass species. *Weed Sci.* 62:433-440.
- Sikkema, P. H., D. E. Robinson, C. Shropshire, and N. Soltani. 2006. Tolerance of otebo bean (*Phaseolus vulgaris*) to new herbicides in Ontario. *Weed Technol.* 20:862-866.
- Sikkema, P. H., D. E. Robinson, R. E. Nurse, and N. Soltani. 2008. Pre-emergence herbicides for potential use in pinto and small red Mexican bean (*Phaseolus vulgaris*) production. *Crop Prot.* 27:124-129.

- Sikkema, P. H., N. Soltani, C. Shropshire, and T. Cowan. 2004a. Tolerance of white beans to postemergence broadleaf herbicides. *Weed Technol.* 18:893-901.
- Sikkema, P. H., N. Soltani, C. Shropshire, and T. Cowan. 2004b. Sensitivity of kidney beans (*Phaseolus vulgaris*) to soil applications of S-metolachlor and imazethapyr. *Can. J. Plant Sci.* 84, 405-407.
- Silvey, B. D., W. E. Mitchem, A. W. Macrae, and D. W. Monks. 2006. Snap bean (*Phaseolus vulgaris*) tolerance to halosulfuron PRE, POST, or PRE followed by POST. *Weed Technol.* 20:873-876.
- Smith J. A. 1986. Dry edible bean field harvesting losses. *Amer. Soc. Agric. Engineer.* 29:1540-1543.
- Smith Jr, R. J., and J. E. Hill. 1990. Weed control technology in US rice. *Pest Management in Rice*. pp, 314-327. Springer Netherlands.
- Soltani, N., C. Gillar, C. J. Swanton, C. Shropshire, and P. H. Sikkema. 2008a. Response of white bean (*Phaseolus vulgaris*) to imazethapyr. *Crop Prot.* 27:672-677.
- Soltani, N., C. Shropshire, and P. H. Sikkema. 2006a. Effects of post-emergence application of bentazon and fomesafen on eight market classes of dry beans (*Phaseolus vulgaris* L.). *Crop Prot.* 25:826-830.
- Soltani, N., C. Shropshire, and P. H. Sikkema. 2012a. Response of dry beans to halosulfuron applied postemergence. *Can. J. Plant Sci.* 92:723-728.
- Soltani, N., C. Shropshire, and P. H. Sikkema. 2012b. Safening effect of bentazon on cloransulam-methyl and halosulfuron-methyl in dry bean. *Agric. Sci.* 3:368-374.

- Soltani, N., C. Shropshire, and P. H. Sikkema. 2013a. Tolerance of mung bean to postemergence herbicides. *Agric. Sci.* 4:558-562.
- Soltani N., C. Shropshire, and P. H. Sikkema. 2015. Response of four market classes of dry beans to halosulfuron applied postemergence at five application timing. *Agric. Sci.* 6:247-255.
- Soltani, N., C. Shropshire, T. Cowan, and P. H. Sikkema. 2003. Tolerance of cranberry beans (*Phaseolus vulgaris*) to soil applications of S-metolachlor and imazetheapyr. *Can. J. Plant Sci.* 18:645-648.
- Soltani, N., C. Shropshire, T. Cowan, and P. H. Sikkema. 2004a. Tolerance of black beans (*Phaseolus vulgaris*) to soil applications of S-metolachlor and imazethapyr. *Weed Technol.* 18:111-118.
- Soltani N., C. Shropshire, T. Cowan, and P. H. Sikkema. 2004b. White bean sensitivity to preemergence herbicides. *Weed Technol.* 18:675-679.
- Soltani N., D. E. Robinson, C. Shropshire, and P. H. Sikkema. 2006b. Adzuki bean (*Vigna angularis*) responses to post-emergence herbicides. *Crop Prot.* 25:613-617.
- Soltani, N., L. L. Eerd, R. Vyn, C. Shropshire, and P. H. Sikkema. 2007. Weed management in dry beans (*Phaseolus vulgaris*) with dimethenamid plus reduced doses of imazethapyr applied preplant incorporated. *Crop Prot.* 26:739-745.
- Soltani, N., M. Kumagai, L. Brown, and P. H. Sikkema. 2010a. Long-spine sandbur [*Cenchrus longispinus* (Hack. in Kneuck.) Fernald] control in corn. *Can. J. Plant Sci.* 90:241-245.

- Soltani, N., R. E. Nurse, and P. H. Sikkema. 2012c. Weed control in dry bean with pendimethalin plus reduced rates of imazethapyr. *Int. Res. J. Agric. Sci. and Soil Sci.* 2:312-317.
- Soltani N., R. E. Nurse, C. Shropshire, and P. H. Sikkema. 2009. Effect of halosulfuron applied preplant incorporated, preemergence, and postemergence on dry bean. *Weed Technol.* 23:535-539.
- Soltani, N., R. E. Nurse, C. Shropshire, and P. H. Sikkema. 2012d. Weed control, environmental impact and profitability of pre-plant incorporated herbicides in white bean. *Amer. J. Plant Sci.* 3:846-853.
- Soltani, N., R. E. Nurse, C. Shropshire, and P. H. Sikkema. 2013b. Response of dry bean to pendimethalin applied preplant incorporated or preemergence. *Acad. J.* 8:4827-4832.
- Soltani, N., R. E. Nurse, C. Shropshire, and P. H. Sikkema. 2014a. Sensitivity of dry bean to dimethenamid-p, saflufenacil and dimethenamid-p/saflufenacil. *Amer. J. Plant Sci.* 5:3288-3294.
- Soltani, N., R. E. Nurse, C. Shropshire, and P. H. Sikkema. 2013c. Weed control in white bean with pendimethalin applied preplant followed by postemergence broadleaved herbicides. *Open Plant Sci. J.* 7:24-30.
- Soltani, N., R. E. Nurse, C. Shropshire, and P. H. Sikkema. 2014b. Weed control in white bean with various halosulfuron tankmixes. *Adv. in Agric.* 2014:1-7.
- Soltani, N., R. E. Nurse, C. Shropshire, and P. H. Sikkema. 2014c. Weed control with

halosulfuron applied preplant incorporated, preemergence or postemergence in white bean. *Agri Sci.* 5:875-881.

Soltani, N., R. E. Nurse, C. Shropshire, and P. H. Sikkema. 2013d. Weed management in white beans with postemergence herbicide tankmixes. *Can. J. Plant Sci.* 93:669-674.

Soltani, N., R. E. Nurse, C. Shropshire, and P. H. Sikkema. 2014d. Weed management in kidney bean with tankmixes of S-metolachlor, imazethapyr and linuron. *Agric. Sci.* 5:611-617.

Soltani, N., R. E. Nurse, D. E. Robinson, and P. H. Sikkema. 2008b. Response of pinto and small red Mexican Beans (*Phaseolus vulgaris* L.) to preplant-incorporated herbicides. *Weed Biol. and Manag.* 8:25-30.

Soltani, N., R. E. Nurse, L. L. Van Eerd, R. J. Vyn, C. Shropshire, and P. H. Sikkema. 2010b. Weed control, environmental impact and profitability with trifluralin plus reduced doses of imazethapyr in dry bean. *Crop Prot.* 29:364-368.

Soltani, N., S. bowley, and P. H. Sikkema. 2005. Responses of black and cranberry beans (*Phaseolus vulgaris*) to post-emergence herbicides. *Crop Prot.* 24:15-21.

Spencer, W. F. and M. M. Cliath. 1974. Factors affecting vapor loss of trifluralin from soil. *Agric. Food Chem.* 22:987-991.

Statistics Canada. 2015. Table 001-0010 - Estimated areas, yield, production and average farm price of field crops, in metric units annual, CANSIM (database). <http://www5.statcan.gc.ca/cansim/a26?lang=eng&retrLang=eng&id=0010010&paSer=&pattern=&stByVal=1&p1=1&p2=-1&tabMode=dataTable&csid=> Accessed:

January 22, 2015.

Stewart, C. L., R. E. Nurse, C. L. Gillard, and P. H. Sikkema. 2010. Tolerance of adzuki bean to preplant-incorporated, pre-emergence, and post-emergence herbicides in Ontario, Canada. *Weed Biol. Manage.* 10:40-47.

Swanton, C. J. and S. F. Weise. 1991. Integrated weed management: the rationale and approach. *Weed Technol.* 5:657-663.

Tinker, N. A. and T. E. Michaels. 1990. Effect of cultivar, planting pattern and harvest method on white bean production. *Annu. Rep. Bean Improv. Coop.* 33:21-22.

Trader, B. W., H. P. Wilson, and T. E. Hines. 2007. Halosulfuron helps control several broadleaf weeds in cucumber and pumpkin. *Weed Technol.* 21:966-971.

Trenkamp, S., W. Martin, and K. Teitjen. 2004. Specific and differential inhibition of very-long-chain fatty acid elongases from *Arabidopsis thaliana* by different herbicides. *National Acad Sci.* 101:11903-11908.

Umeda, K. 1998. Weed control in melons using preemergence and postemergence herbicides. *Proc. West. Soc. Weed Sci.* 51:74.

University of Illinois. 1999. Black Rot of Cabbage and Other Crucifers. *Plant Dis. RPD* 924:1-4.

Urwin, C. P., R. G., Wilson, and D. A. Mortensen. 1996. Responses of dry edible bean (*Phaseolus vulgaris*) cultivars to four herbicides. *Weed Technol.* 10:512-518.

- Van Acker, R.C. A.G. Thomas, J.Y. Leeson, S.Z. Knezevic and B.L. Frick. 2000. Comparison of weed communities in Manitoba ecoregions and crops. *Can. J. Plant Sci.* 80:963-972.
- Van Overbeek J. 1956. Absorption and translocation of plant regulators. *Annu. Review Plant Physiol.* 7: 355-372.
- Vencill, W. K., H. P. Wilson, T. E. Hines, and K. K. Hatzios. 1990. Common lambsquarters (*Chenopodium album*) and rotational crop response to imazethapyr in pea (*Pisum sativum*) and snap bean (*Phaseolus vulgaris*). *Weed Technol.* 4:39-43.
- Vencill, W. K., J. S. Richbury, III, J.W. Wilcut, and L. R. Hawf. 1995. Effect of MON 12037 on purple (*Cyperus rotundus*) and yellow (*Cyperus esculentus*) nutsedge. *Weed Technol.* 9:148-152.
- Wall D. 1995. Bentazon tank-mixtures for improved redroot pigweed (*Amaranthus retroflexus*) and common lambsquarters (*Chenopodium album*) control in navy bean (*Phaseolus vulgaris*). *Weed Technol.* 9:610–616.
- Webster, T. M. 2006. Weed survey: southern states: vegetable, fruit, and nut crops subsection. *Proc. South. Weed Sci. Soc.* 59:260-277.
- Welacky, T. W. and S. J. Park. 1987. Response for row width of white bean lines selected for upright plant type. *Annu. Rep. Bean Improv. Coop.* 30:54.
- Wilson, R. G. 1993. Wild proso millet (*Panicum miliaceum*) interference in dry bean (*Phaseolus vulgaris*). *Weed Sci.* 41:607–610.

- Wilson, R.G. 2005. Response of dry bean and weeds to fomesafen and fomesafen tank mixtures. *Weed Technol.* 19:201-206.
- Wilson R. G. and J. A. Smith. 2002. Influence of harvest-aid herbicides on dry bean (*Phaseolus vulgaris*) desiccation, seed yield, and quality. *Weed Technol.* 16:109-115.
- Wilson, R. G. and S. D. Miller. 1991. Dry edible bean (*Phaseolus vulgaris*) response to imazethapyr. *Weed Technol.* 5:22-26.
- Wilson, R. G., G. A. Wicks, and C. R. Fenster. 1980. Weed control in field beans (*Phaseolus vulgaris*) in western Nebraska. *Weed Sci.* 28:295-299.
- Withgott, J. and Brennan, S. 2008. *Environment: the Science Behind the Stories*. 3rd ed. Pearson Benjamin Cummings, San Francisco, USA.
- Woolley, B. L., T. E. Micheals, M. R. Hall, and C. J. Swanton. 1993. The critical period of weed control in white bean (*Phaseolus vulgaris*). *Weed Sci.* 41:180-184.
- Wyse, D. L., W. F. Meggitt, and D. Penner. 1976. Factors affecting EPTC injury to navy bean. *Weed Sci.* 24:1-4.
- York, A. C., J. W. Wilcut, C. W. Swann, D. L. Jordan, and F. R. Walls. 1995. Efficacy of Imazethapyr in peanut (*Arachis hypogaea*) as affected by time of application. *Weed Sci.* 43:107-116.
- Young, B. G. and S. E. Hart. 1997. Giant foxtail (*Setaria faberi*) control in sethoxydim-resistant corn (*Zea mays*). *Weed Sci.* 45:771-776.
- Zimdahl, R. L., P. Cattizone, and A. C. Butcher. 1984. Degradation of pendimethalin in soil. *Weed Sci.* 32:408-412.

Zyla L. E., R. L. Kushwaha, and A. Vandenberg. 2002. Development of new crop lifter for direct cut harvesting dry bean. *Can. Biosyst. Eng.* 44:9-14.