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Keywords:	Dry bean, efficacy, injury, weed control, yield, Phaseolus vulgaris L.

Managing weeds with herbicides in white bean in Canada: a review

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Abstract: White bean is a high value, important export field crop for farmers in Canada. Effective weed management in white bean is important as this crop is not competitive with weeds. Use of preplant incorporated, preemergence, and postemergence herbicides are effective means for weed control in white bean production in Canada. There are a range of herbicides registered for use on white bean in Canada, but in comparison to other high acreage field crops such as corn and soybean, the options are relatively limited. This can pose challenges for white bean producers trying to use multiple herbicide modes-of-action to reduce the evolution of herbicide resistant weeds, and limits management options for troublesome weeds. In particular, management of perennial weeds in white bean with currently registered herbicides is difficult. There is a continued need to evaluate and register additional herbicide options for weed management in white bean in Canada.

Key words: Dry bean, efficacy, injury, weed control, yield, *Phaseolus vulgaris* L.

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Abbreviations: PP, preplant; PPI, preplant incorporated; **POST**, postemergence; **PRE**, preemergence; **WAA**, weeks after application; **WAE**, weeks after emergence

Introduction

White bean (*Phaseolus vulgaris* L.) is an important global food crop and a lucrative export crop for Canadian farmers [Hensall District Co-operative (HDC) 2009； Statistic Canada 2016]. White bean production can be challenging as the crop is not as robust as soybean and is not considered a competitive crop with weeds (Van Acker et al. 2000). Consequently, weed interference in white bean can have a large impact on net returns for farmers. Reviews of research on weed management research can be useful in respect to approaches to weed management, effectiveness of different weed control programs, and the potential for crop injury. The need for a review on weed management in white bean is necessary as farmers look to diversify their production portfolio with higher value, niche crops like white bean (Desjardins et al. 2010). Reviews can also be useful to researchers because they can show trends in approaches to weed management and identify gaps in weed management that should be the target of future research. There is a substantial body of research on the use of herbicides for weed management in white bean, but there has been no collated review of this work to-date in Canada. The purpose of this review is to summarize research that has been completed to-date on weed management in white bean with herbicides in Canada in order to present the best options for weed management and to identify where further research is needed.

The majority of white bean production in Canada occurs in Ontario and Manitoba. There is limited production in Quebec and Alberta; these two provinces represent approximately 18% of national production. White bean production in

Quebec and Alberta has been declining, with almost no production since 2007 (Statistic Canada 2016). There is no official record of white bean production in any other province in Canada. Since 2007, Ontario and Manitoba comprised almost 100% of the white bean production in Canada (Statistic Canada 2016). During the period from 1998 to 2003, there was greater white bean production in Manitoba than Ontario. In 2000, Manitoba produced 63% (74800 tonnes) and Ontario produced 27% (32000 tonnes) of total Canadian white bean production. After 2003, Ontario production exceeded that in Manitoba, with an average 70% of national white bean production coming from Ontario between 2003 and 2015 and Ontario's portion of national production was as high as 81% (82600 tonnes) in 2010 (Statistic Canada 2016). Seeded area of white bean in Canada increased from 39800 ha in 1998 to 115300 ha in 2002, but decreased after 2002, reaching a low of 18200 ha in 2013. There were 37200 ha of white bean seeded in Canada in 2016 (Statistic Canada 2016). White bean is a relatively high value crop with a farm gate value of $52 million (Canadian dollars) from 68,000 tonnes of white bean produced on 26,300 hectares in 2012 in Ontario (McGee 2016). White bean prices have ranged from $515 to $921 per tonne (Canadian dollars) from 2004 to 2014, which is comparable to the range in soybean ($249 to 517 per tonne) and grain corn ($107 to $260 per tonne) prices over the same period (McGee 2016).

Weed interference negatively affects white bean yield and quality (Radosevich et al. 2007). Some of the common weed species affecting white 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.), barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], and crabgrass (*Digitaria* spp.) (Frick and Thomas 1992; Li et al. 2016a; Li et al. 2016b). Some of the common weed species affecting white bean production in Manitoba include green foxtail [*Setaria viridis* (L.) P. Beauv.], wild oat (*Avena fatua* L.), wild buckwheat (*Polygonum convolvulus* L.), annual smartweed (*Polygonum* spp.), Canada thistle (*Cirsium arvense* L.), common lambsquarters, redroot pigweed, wild mustard, and perennial sow-thistle (*Sonchus arvensis* L.) (Thomas 1991; Wall 1993; Wall 1995). A number of common perennial weeds in Canada also occur in white bean, including Canada thistle, perennial sowthistle, dandelion (*Taraxacum officinale* Weber), and quackgrass [*Elytrigia repens* (L.) Beauv.], for which there are few registered herbicides available for control in white bean in Canada.

White bean is a poor competitor with weeds. Uncontrolled weeds can reduce white bean yield from 48 to 81% (Malik et al. 1993; Chikoye et al. 1995; Soltani et al. 2014a, b; Li et al. 2016a, b). In addition, weeds can affect harvest efficiency and lower white bean quality due to seed staining (Chikoye et al. 1995). Time of weed emergence relative to the growth stage of white bean influences the extent of yield loss. The critical period of weed control is extremely important in white bean production (Swanton and Weise 1991). Dawson (1964) reported that weeds which appeared in the first 4 and 5 weeks of the growing season resulted in significant yield loss in white bean. Woolley et al. (1993) reported that the critical period of weed control in white bean was from the second trifoliate to the first flower stage based on studies conducted in Ontario. White bean yield and quality are therefore dependent on good weed management.

Results of Herbicide Efficacy Trials

Herbicide efficacy research completed to-date on white bean in Canada includes studies on a range of herbicide with several modes-of-action. In addition, the research includes herbicides applied preplant incorporated (PPI), preemergence (PRE), and postemergence (POST). The work lends itself to categorical presentation both in terms of application timing and in terms of herbicide modes-of-action. The latter is of increasing importance due to the increasing selection of herbicide resistant weed biotypes in Canada. The results represented are in both categories; according to application timing in the Tables and according to herbicide mode-of-action in the discussion.

Trifluralin and Pendimethalin (PPI)

Trifluralin [α,α,α-trifluro-2,6-dinitro-N,N-dipropyl-p-toluidine] and pendimethalin [N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine] are group 3 herbicides that inhibit microtubule polymerization and control annual grasses and some annual broadleaf weeds in white bean (Zimdahl et al. 1984; Senseman 2007). Trifluralin must be applied preplant incorporated (PPI) and incorporated within 24 hours to reduce losses by photodegradation and volatilization (Spencer and Cliath

1974). In white bean, trifluralin (PPI) and pendimethalin (PPI) provide control of barnyardgrass, smooth crabgrass [*Digitaria ischaemum* (Schreb) Muhl.], fall panicum (*Panicum dichotomiflorum* Michx.) and foxtail species (Table 1 and 2). In addition, common lambsquarters and redroot pigweed are suppressed by these herbicides (Betts and Morrison 1979; Ferrell et al. 2003; Soltani et al. 2013b). Trifluralin is also effective for controlling wild oat. Wild oat density was decreased 66 to100% with trifluralin (PPI) in faba bean in Manitoba (Betts and Morrison 1979). Trifluralin and pendimethalin may cause injury to white bean under cold, wet conditions. Injury symptoms may include swollen root tips, hypocotyl swelling and cracking, stunted growth, and delayed white bean emergence (Senseman 2007). Injury occurs more frequently in light textured soils with low organic matter (OM), since these herbicides are more biologically available in these soils (Morrison et al. 1989; Gunsolus and Curran 1999).

In a number of studies, trifluralin (PPI) and pendimethalin (PPI) provided lower levels of control of common lambsquarters (60 and 56%) (Soltani et al. 2010b; Soltani et al. 2012b; Li et al. 2016b). This may be attributed to heavy textured soils with high organic matter (OM) content or very high densities of common lambsquarters. Higher rates of these two herbicides are recommended on high clay content soils with high OM content, and when weed densities are high (Senseman 2007).

EPTC (PPI)

EPTC (S-ethyl N,N-dipropylthiocarbamate) is a group 8 herbicide; a cell growth disruptor and inhibitor that provides control of annual grasses and some annual broadleaf weeds in white bean (Senseman 2007). EPTC is highly volatile and should be incorporated immediately after application (Gray 1965). Many annual grasses are controlled by EPTC, including barnyardgrass, crabgrass and foxtail species. EPTC also has some activity on ladysthumb (*Polygonum persicaria* L.), common lambsquarters, common chickweed (*Stellaria media* L.) and redroot pigweed (Soltani et al. 2012b). Wild mustard is not well controlled by EPTC. Friesen (1987) reported that EPTC only provided 33% control of wild mustard in a four-year weed management experiment in sunflower. Moisture stress, soil compaction, deep planting and damaged seeds all increase the potential for EPTC injury on white bean (Wyse et al. 1976). Injury symptoms include crinkled and malformed leaves, bud-seal, stunting, and necrotic growing point (Urwin et al. 1996).

Dimethenamid-P and S-metolachlor (PPI and PRE)

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. The group 15 herbicides that inhibit very long chain fatty acid biosynthesis and provide control of annual grasses in white bean (Trenkamp et al. 2004; Senseman 2007). Dimethenamid-P and S-metolachlor can be applied PPI or PRE in white bean (Sikkema et al. 2008; PMRA 2009). These herbicides provide control of some annual grasses, including barnyardgrass, crabgrass, foxtail species, and witchgrass (*Panicum capillare* L.) (Sikkema et al. 2008; Soltani et al. 2012b) (Tables 1 and 2).

They also provide control of nightshades and redroot pigweed (Soltani et al. 2012b; Hutchinson 2012) (Tables 1 and 2). However, they are not as efficacious on fall panicum, proso millet (*Panicum miliaceum* L.), and long-spined sandbur [*Cenchrus longispinus* (Hack.) Fern.] (Soltani et al. 2010a). Both dimethenamid-P and S-metolachlor provide excellent green foxtail and redroot pigweed control (Table 1 and 2). Dimethenamid-P and S-metolachlor provided better control of redroot pigweed than common lambsquarters or wild mustard when applied PPI or PRE (Li et al. 2016b; Soltani et al. 2014a).

Pyroxasulfone is another group 15 herbicide which has been evaluated for weed control in white bean but it is not yet registered in Canada. Pyroxasulfone applied PRE, provides similar weed control to dimethenamid-P and S-metolachlor. Tazier et al (2016c) reported that pyroxasulfone (PRE), dimethenamid-P (PRE) and S-metolachlor (PRE) provided similar control of redroot and green pigweed (98%) and green foxtail but superior control of wild mustard control (63-95%) compared to dimethenamid-P (16-48%) and S-metolachlor (2-33%) (Table 2). Similar to dimethenamid-P and S-metolachlor, pyroxasulfone provided poor control of common ragweed (28-39%) (Taziar et al. 2016c).

The group 15 herbicides cause greater white bean injury on coarse-textured, low OM soils and in cold, wet conditions; in part, because it takes longer for white beans to emerge, which delays herbicide metabolism. Crop injury symptoms include chlorosis followed by necrosis of the cotyledons, unifoliate and first trifoliate leaves, and a delay in plant growth (Poling et al. 2009). There is greater potential for injury to white bean when dimethenamid-P and S-metolachlor are applied PRE than PPI, and the small seeded dry bean market classes, including white bean, are more susceptible than the large seeded market classes (Soltani et al. 2007; Soltani et al. 2014c). Taziar et al. (2016a) reported lower than 10% white bean injury with pyroxasulfone applied PRE at 100 and 200 g ai ha^{-1}.

Imazethapyr (PPI and PRE)

Imazethapyr [2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid] is a group 2 imidazolinone herbicide that inhibits acetolactate synthase (ALS), an enzyme involved in the biosynthesis of branched chain amino acids (Brown 1990) including valine, leucine, and isoleucine (Senseman 2007; Duggleby et al. 2008).. Imazethapyr is absorbed by both the roots and foliage of developing weed seedlings and can be applied PPI or PRE in white bean (Bauer et al. 1995b). Imazethapyr provides season-long residual weed control (Vencill et al. 1990) of many broadleaf weeds, including wild buckwheat (*Polygonum convolvulus* L.), ladysthumb, common lambsquarters, mustard species, nightshade species, pigweed species and velvetleaf (Table 1). The efficacy of imazethapyr on common ragweed and common lambsquarters is inconsistent (Bauer et al. 1995b; York et al. 1995). Annual grasses, including foxtail, barnyardgrass, crabgrass and witchgrass, can also be controlled with imazethapyr. In white bean, the efficacy of imazethapyr (PPI) on barnyardgrass ranged from 13 to 91% (Table 1). Control is influenced by the time after application, for example, Soltani et al. (2012a) reported 13% control 4 WAE and in the same trial

91% control 8 WAE when imazethapyr applied PPI. Barnyardgrass control improved as the rate of imazethapyr rate was increased, however, excellent barnyardgrass control with imazethapyr usually requires a grass herbicide tank mix (Arnold et al. 1993; Soltani et al. 2010b). There have been no published studies on the use of imazethapyr applied POST in white bean in Canada.

There is potential for imazethapyr to injure white bean when it is applied at higher rates (70 to 100 g ai ha^{-1}) (Renner and Powell 1992; Wilson and Miller 1991; Arnold et al. 1993; Bauer et al. 1995b; Blackshaw and Saindon 1996; Soltani et al. 2004a, b; Soltani et al. 2007). Cold, wet conditions can increase white bean injury from imazethapyr (BASF 2011).

Halosulfuron-methyl (PPI, PRE, and POST)

Halosulfuron-methyl (methyl 3-chloro-5-[[[[(4, 6-dimethoxy-2-pyrimidinyl) amino] carbamoyl]amino]sulfonyl]-l-methyl-1H-pyrasole-4-carboxylate) is a group 2 sulfonylurea herbicide (Senseman 2007). Halosulfuron is considered safe to use on white bean (Soltani et al. 2012c).

Halosulfuron applied PPI or PRE provides excellent control of common lambsquarters, redroot pigweed, common ragweed, and wild mustard (Tables 1 and 2). Not only weed control ratings, but also density, dry weight of those weeds had been reduced over 90% (Li et al. 2016a,b). Since halosulfuron does not control grasses (Buker et al. 1998), it can be combined with a grass herbicide for broad spectrum weed control (Li et al. 2016a,b). More information about tankmixes halosulfuron with a grass herbicides will be discussed in tankmixes section.

Halosulfuron (27 g ai ha^{-1}) applied PRE, provided control of morningglory species in cucumber (Trader et al. 2007) and velvetleaf in pumpkin (Brown and Masiunas 2002). Velvetleaf is common on some Ontario farms. Thus, halosulfuron could be a potential herbicide to control these two weeds in white bean. More research needs to be conducted in white bean field to ascertain the efficacy of halsosulfuron on velvetleaf.

Halosulfuron, applied POST, provides 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. (2013a). 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 (Boydston 2007). In many cases, halosulfuron should be combined with other herbicides for broad spectrum broadleaf weed control when applied POST. Halosulfuron applied POST provides poor control of grass weeds. Buckelew (2005) reported that halosulfuron had no effect on large crabgrass, goosegrass or fall panicum. Halosulfuron is more efficacious on annual broadleaf weeds when applied PPI or PRE than POST (Tables 1, 2 and 3).

Soltani et al. (2009) evaluated the crop safety of halosulfuron applied at 35 and 70 g ai ha^{-1} applied PPI, PRE, and POST to white bean in Harrow, Ridgetown, and Exeter, Ontario. They found that halosulfuron applied PPI, PRE, and POST caused only 1, 2, and 5% crop injury, respectively. The injury symptoms caused by halosulfuron included minor chlorosis, necrosis, stunting, and in rare, but extreme cases, death of the growing point.

Sulfentrazone (PRE)

Sulfentrazone is a soil applied, group 14, triazolinone herbicide that inhibits protoporphyrinogen IX oxidase (PPO) and is used for broadleaf weed control in white bean, but is not registered for use in Canada. Taziar et al. (2016a,b,c,d,e) conducted several studies with this herbicide in white bean. They reported that sulfentrazone applied PRE at 140 and 210 g ai ha^{-1} provided excellent redroot pigweed, green pigweed, and common lambsquarters control and moderate control of barnyardgrass and green foxtail (Table 2). They found that these treatments did not provide good control of either common ragweed or wild mustard (0-35%). The addition of imazethapyr to sulfentrazone improved wild mustard and green foxtail control, but control of common ragweed and barnyardgrass was marginal (Taziar et al. 2016e). The addition of S-metolachlor to sulfentrazone improved barnyardgrass and green foxtail control, but not common ragweed and wild mustard control (Taziar et al. 2016 b, e). The addition of halosulfuron to sulfentrazone increased the control of common ragweed and wild mustard (Taziar et al. 2016b). The addition of halosulfuron and S-metolachlor to sulfentrazone provided excellent control of green and redroot pigweed, common ragweed, common lambsquarters, wild mustard, and green foxtail, but it caused 10 to 12% and 22 to 23% white bean injury at the 140 and 210 g ai ha^{-1} sulfentrazone rates, respectively (Taziar et al. 2016b). Sulfentrazone applied alone or tankmixed with pendimethalin, dimethenamid-P, S-metolachlor, or pyroxasulfone provides excellent control of green and redroot pigweed, common lambsquarters, and green foxtail in white bean (Taziar et al. 2016a). It is not safe to apply sulfentrazone to white bean at rates of 280 and 420 g ai ha^{-1} (Taziar et al. 2016d). Lower rates of sulfentrazone (140 g ai ha^{-1}) must be used in white bean.

Quizalofop-p-ethyl, fenoxaprop-p-ethyl, fluazifop-p-butyl, sethoxydim, and clethodim (POST)

Quizalofop-p-ethyl [(R)-2-[4-[(6-chloro-2-quinoxalinyl)oxy]phenoxy]propanoic acid], fenoxaprop-p-ethyl [(+)-2-[4-[(6-chloro-2-benzoxazolyl)oxy] phenoxy]propanoic acid], fluazifop-p-butyl [(R)-2-[4-[[5-(trifluoromethyl) -2-pyridinyl]oxy]phenoxy]propanoic acid] sethoxydim [2-[1-(ethoxyimino)butyl] -5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one], and clethodim [(E,E)-(+)-2-[1-[[(3-chloro-2-propenyl)oxy]imino]propyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one] are group 1 herbicides that inhibit Acetyl-Coenzyme A Carboxylase (ACCase) and provide POST control of annual and perennial grasses in a range of broadleaf crops including white bean (Senseman 2007). The annual grasses controlled by these herbicides include barnyardgrass, crabgrass, fall panicum, foxtail species, proso millet and witchgrass. The perennial grass, quackgrass, can also been controlled by some of these herbicides (Linscott and Vaughan 1990; Young and Hart 1997; McCullough et al. 2011). These herbicides are applied POST when annual grasses are in the two to five leaf stage (Soltani et al. 2006b). The efficacy of these 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 soil so grasses that emerge after application are not controlled (Scott et al. 1998; Baumann 2008).

There have been few peer-reviewed published studies on the use of these herbicides in white bean in Canada (Table 3). A few crop tolerance studies have been published and typically white bean tolerance is very good. Soltani et al. (2015) found that quizalofop-p-ethyl applied alone or combination with biostimulants (Crop Booster or RR Soybooster) caused less than 3% injury to white bean.

Bentazon (POST)

Bentazon, 3-(1-methylethyl)-(1H)-2,1,3-benzothiadiazin-4(3H)-one 2,2-dioxide, is a selective, benzothiadiazole, group 6, photosynthesis inhibiting herbicide (Blackshaw et al. 2000; Senseman 2007). Bentazon provides control of common lambsquarters, ladysthumb, mustard species, velvetleaf, common cocklebur (*Xanthium strumarium* L.), and nutsedge (*Cyperus* spp.), (PMRA 2008) (Table 3). Weed control efficacy with bentazon is influenced by the size of the weeds at the time of application. Weed control decreases as the size of the weeds at the time of application increases (Andersen et al. 1974), with large weeds often escaping control. Bentazon provides better weed control when weeds are young and actively growing and it is safe for use on white bean if applied after the first trifoliate stage. Bentazon provided better common lambsquarters and wild mustard control than redroot pigweed and common ragweed (Table 3). It has no effect on green foxtail (Table 3). There has been substantive efficacy work with bentazon in crops other than white bean. Bauer et al. (1995a) reported bentazon provided only 30% control of redroot pigweed but over 90% control of common lambsquarters in soybean. Wall (1995) reported common lambsquarters density was reduced over 90% when bentazon was applied at 1080 g ai ha^{-1} and the density of redroot pigweed was reduced from 63 to 97%. Bentazon has no residual activity in soil, so weeds that emerge after application are not controlled (Smith and Hill 1990).

Bentazon can injure white bean under hot, humid conditions and when it is tank mixed with 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).

Fomesafen (POST)

Fomesafen, 5-[2-chloro-4-(trifluoromethyl) phenoxy]-N-(methylsulfonyl) -2-nitrobenzamide, is a group 14, diphenyl ether, protoporphyrinogen IX oxidase (PPO) inhibitor, POST broadleaf herbicide (Soltani et al. 2006a; Senseman 2007). Fomesafen provides control of mustard species, pigweed species, common ragweed, ladysthumb, wild buckwheat and annual nightshades, but is weak on cocklebur, common lambsquarters and velvetleaf (Wilson 2005; Peachey et al. 2012) (Table 3). Fomesafen provides short residual broadleaf weed control.

Fomesafen can cause injury to white bean where injury symptoms include speckling, bronzing, burning or crinkling of the leaves (Wilson 2005). There is greater potential for white bean injury from fomesafen if there are spray overlaps or if fomesafen is applied at above label rates (Soltani et al. 2006a).

Tankmixes

Herbicides applied PPI or PRE in white bean, frequently combine a grass herbicide such as trifluralin, pendimethalin, EPTC, dimethenamid-P, or S-metolachlor with a broadleaf herbicide such as imazethapyr or halosulfuron for broad spectrum weed control. Most studies of herbicide tank mixes for weed management in white bean are related to those herbicides. 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 lambquarters, wild mustard, common ragweed and green foxtail was reduced. Compared to imazethapyr (15 g ai ha^{-1}) applied alone, the level of control of redroot pigweed, common lambsquarters and green foxtail was much higher when it was tankmixed with dimethenamid-P. When imazethapyr was tankmixed with trifluralin, the dose of imazethapyr required was reduced for green foxtail, common lambsquarters and common ragweed control (Soltani et al. 2010b). Excellent common lambsquarters, wild mustard, redroot pigweed, common ragweed, and green foxtail control was provided when halosulfuron was tankmixed with either trifluralin, pendimethalin, EPTC, dimethenamid-P, or S-metolachlor (Li et al 2016a, b). Generally, the tankmix of S-metolachlor plus imazethapyr is safe for use in white bean, but serious crop injury may occur under some environmental conditions (Soltani et al. 2004a).

A tank mix of bentazon plus fomesafen applied POST in white bean provides control of common lambsquarters, wild buckwheat, annual nightshades, ladysthumb, wild mustard, pigweed species, common ragweed and velvetleaf (Wilson 2005). The tankmix of halosulfuron and bentazon applied POST provided over 80% control of redroot pigweed, common ragweed, and common lambsquarters (Soltani et al. 2013a). Pendimethalin followed by (fb) bentazon, pendimethalin fb fomesafen, pendimethalin fb bentazon+fomesafen, and pendimethalin fb halosulfuron are examples of herbicide sequential treatments that have been studied for use in white bean (Soltani et al. 2013b).

The tankmix of bentazon plus fomesafen provides broad spectrum broadleaf weed control in white bean but the level of crop injury is influenced by weather conditions (Sikkema et al. 2004; Soltani et al. 2005). Soltani et al. (2012d) found halosulfuron-methyl and bentazon mixtures caused injury in black, white, cranberry and kidney bean shortly after application, but plants recovered with no reduction in plant height, shoot dry weight, and yield. The addition of bentazon to halosulfuron did not result in greater crop injury (Soltani et al. 2012b).

There has been one study investigating tank mixing insecticides and herbicides for combined insect and weed management in white bean. Soltani et al. (2012e) reported that tank mixing dimetholate or cyhalothrin-lambda insecticides with sethoxydim or quizalofop-p-ethyl did not decrease efficacy on either green or giant foxtail. They also reported that tank mixing dimetholate insecticide with bentazon did not decrease the control of redroot pigweed compared to bentazon alone and that the control of redroot pigweed was improved when cyhalothrin-lambda insecticide was tank mixed with bentazon.

Gaps in Research

When considering the research that has been conducted on herbicide based weed management in white bean in Canada there are some gaps. Weather conditions are a critical factor in herbicide efficacy and although for most studies soil characteristics were provided, in many cases weather details at time of application and through the remainder of the growing season were not included. Details on the weather conditions before, at, and after application would be useful to better understand differences in efficacy or crop injury among the numerous studies conducted. In addition, with the appropriate background information it is easier to determine whether the results are broadly applicable. For example, group 15 herbicides required rainfall within 10 days after application to facilitate uptake by developing weed seedlings (Senseman 2007). In addition, it is always useful if details are provided in relation to variable weed efficacy ratings. For example, in the study by Wall (1995) redroot pigweed and common lambsquarters control with imazethapyr was much lower in 1994 compared to 1992 and 1993, which was attributed to a second flush of weed emergence in the 1994 trials which did not occur in 1992 or 1993.

In white bean producing areas in Canada, there are many herbicide resistant weeds. Green foxtail is one of the most abundant weeds in Canada and this includes white bean production areas in Manitoba and Ontario (Thomas et al. 1988; Frick and Thomas 1992; Leeson et al. 2005) (Tables 1-3). Trifluralin-resistant green foxtail was reported in Manitoba in 1989 (Morrison et al. 1989) and more recently green foxtail populations have been identified that are resistant to many herbicides used in white bean production including fenoxaprop-p-ethyl, quizalofop-p-ethyl, sethoxydim, and clethodim (Beckie 2014). Wild oat, a very common weed in Manitoba (Thomas et al. 1988) has many populations resistant to a range of herbicides used in white bean production including fenoxaprop-p-ethyl, quizalofop-p-ethyl, sethoxydim, and clethodim. There are kochia [*Kochia scoparia* (L.) Schrad.] populations resistant to group 2 herbicides including imazethapyr (Morrison and Devine 1994; Guttieri et al. 1995) and kochia is another common weed in Manitoba's white bean production region (Leeson et al. 2005). Many group 2 resistant weeds have also 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). Repeated use of a single herbicide mode-of-action contributes to the evolution of herbicide resistant weed biotypes (Powles et al. 1997). Herbicide rotation and herbicide tankmixes may delay the evolution of resistant weeds, so the inclusion of multiple herbicide modes-of-action is more sustainable (Beckie 2006). Given the threat from, in particular, group 1 and group 2 resistant weeds in white bean production areas, farmers need new herbicide modes-of-action for weed management in white bean and this is an area that requires more active research.

Canada thistle, sowthistle, field bindweed, and quackgrass are the common perennial weeds on the Canada prairies and in Ontario (OMAFRA 2004; AAFC 2005; Leeson et al. 2005) including in white bean production areas. Interference from perennial weeds can substantially reduce white bean yield. Zollinger and Kells (1993) reported white yield decreases of 48 and 36% due to perennial sowthistle at 82 and 90 shoots per m^2, respectively. There has been very little additional research conducted on perennial weed management in white bean. Tillage, crop rotation and efficacious herbicides are components of a perennial weed management strategy in white bean. Fall burndown or spring preplant applications of glyphosate, can be an effective control for many perennial weed species (Cowbrough 2005).

Conclusions

Although reduced herbicide use has been promoted by farmers, environmentalists and consumers, herbicides are still the most widely used pesticide in Canada and they are used on the vast majority of annual field crop hectares in Canada (Nazarko et al. 2005). As such, farmers need current research results to understand the effect of herbicide choice, herbicide rate, herbicide tankmixtures, and herbicide application timing so that they can develop optimal, field specific weed management programs - this is as true in white bean as it is in other field crops. The results of this review show that several PPI, PRE and POST herbicides can be used in white bean. However, usually one herbicide does not control all the weed species infesting white bean fields in Canada. Herbicide tankmixtures are recommended for effective broad spectrum weed control, application efficiency, and herbicide resistant weed management. In this regard, there is a particular need for efficacy studies on the use of group 2 herbicide tank-mix options in white bean. In general, although there are a range of published herbicide efficacy studies in white bean in Canada, there is often a substantive range in efficacy within these studies and yet in many cases limited descriptions within these studies as to the reasons for the range in efficacy. In addition, there is little information available on the efficacy of available registered herbicide options in white bean in Canada on common perennial weeds. White bean is, and will remain, an important high value export crop for Canadian farmers and herbicide-based weed control in white bean will continue to be a priority for these farmers. This review shows that although there are herbicide options for farmers the options are not sufficient especially in light of concerns around broad spectrum weed control, the evolution of herbicide resistant weeds, herbicide mode-of-action rotation, and the management of perennial weeds.

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Table 1. Weed control efficacy results for herbicides applied preplant incorporated (PPI) in white bean in Canada.

Herbicide	Weed Type	Weeds	Efficacy range (%)	Citation
Trifluralin	Grass	Green foxtail	94-100	Li et al. 2016b; Soltani et al. 2010b; Soltani et al. 2012a-b; Soltani et al. 2014a
	Broadleaf	Common lambsquarters	60-92	Li et al. 2016b; Soltani et al. 2010b; Soltani et al. 2012a-b; Soltani et al. 2014a
		Redroot pigweed	72-98	Li et al. 2016b; Soltani et al. 2010b; Soltani et al. 2012 a-b; Soltani et al. 2014a
		Wild mustard	11-44	Li et al. 2016b; Soltani et al. 2012 a-b; Soltani et al. 2014a
		Common ragweed	9-28	Li et al. 2016b; Soltani et al. 2012 a-b; Soltani et al. 2010b; Soltani et al. 2014a
	Grass	Barnyardgrass	58	Soltani et al. 2012a
		Green foxtail	92-98	Li et al. 2016b; Soltani et al. 2013b
	Broadleaf	Common lambsquarters	56-97	Li et al. 2016b; Soltani et al. 2012 a-b; Soltani et al. 2013b
		Redroot pigweed	91-98	Li et al. 2016b; Soltani et al. 2012 a-b; Soltani et al. 2013b
		Wild mustard	0-23	Li et al. 2016b; Soltani et al. 2012 a-b; Soltani et al. 2013b
		Common ragweed	1-13	Li et al. 2016b; Soltani et al. 2012 a-b; Soltani et al. 2013b
EPTC	Grass	Green foxtail	94-99	Li et al. 2016b; Soltani et al. 2012b
	Broadleaf	Common lambsquarters	77-85	Li et al. 2016b; Soltani et al. 2012b
		Redroot pigweed	73-78	Li et al. 2016b; Soltani et

				al. 2012b
		Wild mustard	24-68	Li et al. 2016b; Soltani et al. 2012b
		Common ragweed	52-71	Li et al. 2016b; Soltani et al. 2012b
Dimethenamid-P	Grass	Green foxtail	95-96	Li et al. 2016b;
	Broadleaf	Common lambsquarters	55-72	Li et al. 2016b;
		Redroot pigweed	93-97	Li et al. 2016b;
		Wild mustard	27-70	Li et al. 2016b;
		Common ragweed	41-56	Li et al. 2016b;
S-metolachlor	Grass	Green foxtail	93-97	Li et al. 2016b; Soltani et al. 2014a
	Broadleaf	Common lambsquarters	19-82	Li et al. 2016b; Soltani et al. 2014a
		Redroot pigweed	84-95	Li et al. 2016b; Soltani et al. 2014a
		Wild mustard	11-55	Li et al. 2016b; Soltani et al. 2014a
		Common ragweed	13-40	Li et al. 2016b; Soltani et al. 2014a
Imazethapyr	Grass	Green foxtail		
		Barnyardgrass	13-91	Soltani et al. 2012a
	Broadleaf	Common lambsquarters	78-100	Soltani et al. 2012a; Soltani et al. 2014a
		Redroot pigweed	62-99	Soltani et al. 2012a; Soltani et al. 2014a
		Wild mustard	96	Soltani et al. 2014a
		Common ragweed	73-97	Soltani et al. 2012a; Soltani et al. 2014a
Halosulfuron	Grass	Green foxtail	47-59	Li et al. 2016b; Soltani et al. 2014a
	Broadleaf	Common lambsquarters	96-100	Li et al. 2016b; Soltani et al. 2014a,b
		Redroot pigweed	83-100	Li et al. 2016b; Soltani et al. 2014a,b
		Wild mustard	99-100	Li et al. 2016b; Soltani et al. 2014a,b
		Common ragweed	95-99	Li et al. 2016b; Soltani et al. 2014a

Table 2. Weed control efficacy results for herbicides applied preemergence (PRE) in white bean in Canada.

Herbicide	Weed Type	Weeds	Efficacy range (%)	Citation
Pendimethalin	Grass	Green foxtail	80-88	Li et al. 2016a; Taziar et al. 2016c
	Broadleaf	Common lambsquarters	84-98	Li et al. 2016a; Taziar et al. 2016c
		Redroot and green pigweed	59-69	Li et al. 2016a; Taziar et al. 2016c
		Wild mustard	13-48	Li et al. 2016a; Taziar et al. 2016c
		Common ragweed	9,92	Li et al. 2016a; Taziar et al. 2016c
Dimethenamid-P	Grass	Green foxtail	92-99	Li et al. 2016a; Taziar et al. 2016c
	Broadleaf	Common lambsquarters	18-52	Li et al. 2016a; Taziar et al. 2016c
		Redroot and green pigweed	96-100	Li et al. 2016a; Taziar et al. 2016c
		Wild mustard	16-57	Li et al. 2016a; Taziar et al. 2016c
		Common ragweed	19-41	Li et al. 2016a; Taziar et al. 2016c
S-metolachlor	Grass	Green foxtail	93-99	Li et al. 2016a; Taziar et al. 2016b,c
	Broadleaf	Common lambsquarters	7-27	Li et al. 2016a; Taziar et al. 2016b,c
		Redroot and green pigweed	89-100	Li et al. 2016a; Taziar et al. 2016b,c
		Wild mustard	2-50	Li et al. 2016a; Taziar et al. 2016b,c
		Common ragweed	3-27	Li et al. 2016a; Taziar et al. 2016b,c
Imazethapyr	Grass	Barnyardgrass	49-69	Taziar et al. 2016e
		Green foxtail	85-92	Taziar et al. 2016e
	Broadleaf	Common lambsquarters	97-99	Taziar et al. 2016e
		Redroot and green	87-92	Taziar et al. 2016e

		pigweed		
		Wild mustard	97-99	Taziar et al. 2016e
		Common ragweed	23-37	Taziar et al. 2016e
Halosulfuron	Grass	Green foxtail	11-53	Li et al. 2016a; Taziar et al. 2016b
	Broadleaf	Common lambsquarters	87-99	Li et al. 2016a; Soltani et al. 2014b; Taziar et al. 2016b
		Redroot and green pigweed	89-100	Li et al. 2016a; Soltani et al. 2014b; Taziar et al. 2016b
		Wild mustard	98-100	Li et al. 2016a; Soltani et al. 2014b; Taziar et al. 2016b
		Common ragweed	83-96	Li et al. 2016a; Taziar et al. 2016b
Pyroxasulfone[a]	Grass	Green foxtail	97-98	Taziar et al. 2016c
	Broadleaf	Common lambsquarters	49-54	Taziar et al. 2016c
		Redroot and green pigweed	98	Taziar et al. 2016c
		Wild mustard	63-95	Taziar et al. 2016c
		Common ragweed	28-39	Taziar et al. 2016c
Sulfentrazone[a]	Grass	Barnyardgrass	73-86	Taziar et al. 2016e
		Green foxtail	45-90	Taziar et al. 2016b,c,e
	Broadleaf	Common lambsquarters	100	Taziar et al. 2016b,c,e
		Redroot and green pigweed	98-100	Taziar et al. 2016b,c,e
		Wild mustard	2-80	Taziar et al. 2016b,c,e
		Common ragweed	4-24	Taziar et al. 2016b,c,e

[a]Not registered in white bean in Canada.

Table 3. Weed control efficacy results for herbicides applied postemergence (POST) in white bean in Canada.

Herbicide	Weed Type	Weed controlled	Efficacy range (%)	Citation
Quizalofop-p-ethyl	Grass	Green foxtail	74-98	Soltani et al. 2012e
		Giant foxtail	91-97	Soltani et al. 2012e
	Broadleaf	-		
Fenoxaprop-p-ethyl	Grass	-[a]		
	Broadleaf	-		
Fluazifop-p-butyl	Grass	-		
	Broadleaf	-		
Sethoxydim	Grass	Green foxtail	84-98	Soltani et al. 2012e
		Giant foxtail	91-98	Soltani et al. 2012e
	Broadleaf	-		
Clethodim	Grass	-		
	Broadleaf	-		
Bentazon	Grass	Green foxtail	0	Blackshaw et al. 2000; Soltani et al. 2013b
		Barnyardgrass	0	Blackshaw et al. 2000
	Broadleaf	Common lambsquarters	85-90	Soltani et al. 2013a,b
		Redroot pigweed	54-76	Soltani et al. 2013a,b
		Wild mustard	96-97	Soltani et al. 2013b
		Common ragweed	50-66	Soltani et al. 2013a,b
		Wild buckwheat	70-85	Blackshaw et al. 2000
		Green smartweed	70-95	Blackshaw et al. 2000
		Hairy nightshade	80-95	Blackshaw et al. 2000
Fomesafen	Grass	Green foxtail	23-65	Soltani et al. 2013b
	Broadleaf	Common lambsquarters	53-75	Soltani et al. 2013a,b
		Redroot pigweed	85-99	Soltani et al. 2013a,b
		Wild mustard	100	Soltani et al. 2013b
		Common ragweed	90-98	Soltani et al. 2013a,b
Halosulfuron	Grass	Green foxtail	0-1	Soltani et al. 2013b
	Broadleaf	Common lambsquarters	8-41	Soltani et al. 2013a,b; Soltani et al. 2014b
		Redroot pigweed	54-100	Soltani et al. 2013a,b; Soltani et al. 2014b
		Wild mustard	100	Soltani et al. 2013b; Soltani et al. 2014b
		Common ragweed	91-99	Soltani et al. 2013 a,b

[a]No published weed control efficacy experiments in white bean in Canada.