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Global expansion in the cultivation of genetically engineered (GE) crops has raised concerns about the adventitious presence of GE seeds in non-GE and organic products. Flax is the second most important oilseed crop in western Canada and is currently being evaluated as a potential platform for the production of bio-products. Before transgenic flax is released for commercial production, mitigation measures must be identified to reduce the adventitious presence in subsequent crops. To quantify adventitious presence of volunteer flax in spring wheat and to identify the efficacy of herbicide treatments on mitigating volunteer flax adventitious presence, research was conducted at four locations during 2005 and 2006 in central Alberta. To simulate artificial volunteer populations, flax was seeded prior to wheat at a target population of 150 plants m^{-2}. In the untreated control, volunteer flax seed yield was 135 kg ha^{-1}, which resulted in adventitious presence of 8.57% in spring wheat. When left uncontrolled, volunteer flax reduced wheat yields ~57% and resulted in volunteer flax seed production of 4,755 seeds m^{-2}. A single PRE treatment of glyphosate or glyphosate plus tribenuron reduced volunteer flax density from 39 to 4 and 6 plants m^{-2}, respectively, seed production from 4,755 to < 58 seeds m^{-2}, and volunteer flax seed viability from 55 to < 40%. POST herbicides, fluroxypyr plus MCPA and fluroxypyr plus 2,4-D, reduced volunteer flax seed production as low as 0.6 and 0.0 seeds m^{-2}, respectively, adventitious presence to 0.64 and 0.03%, respectively, and seed viability to ≤ 10%. Combination of glyphosate applied PRE followed by fluroxypyr plus 2,4-D or by thifensulfuron plus tribenuron plus quinclorac applied POST reduced adventitious presence of volunteer flax in wheat to near 0%. These treatment combinations were also effective for reducing volunteer flax fecundity to 0.0 and 7.1 seeds m^{-2}, respectively, and volunteer flax seed viability to 0 and 5%, respectively. This study demonstrated that with effective mitigation strategies, seed mediated gene flow from GE volunteer flax can be reduced.

Nomenclature: 2,4-D; fluroxypyr; glyphosate; MCPA; quinclorac; thifensulfuron; tribenuron; flax, *Linum usitatissimum* L.; wheat, *Triticum aestivum* L.

Key words: Commingling, mitigation, seed mediated gene flow, volunteer flax.

Growers have rapidly adopted crops derived from recombinant DNA technology (Brookes and Barfoot 2008). In 2008, ~13.3 million farmers planted transgenic crops in 25 countries on an estimated area of 125 million hectares (James 2008). Abiotic stress resistant crops are currently under development and have the potential to enhance crop productivity and environmental sustainability (Warwick et al. 2009). Widespread cultivation of GE crops and the continued reluctance of some members of the European Union (EU) to accept GE seeds for human and animal consumption increases concerns about pollen- and seed-mediated gene flow. Adventitious presence of GE seeds in conventional crops may jeopardize coexistence of transgenic, conventional, and organic cropping systems (Devos et al. 2009; Mallory-Smith and Zapiola 2008) and impact the market and trade of seeds from non-GE crops (Demeke et al. 2006; Gaines et al. 2007; Kershen and McHughen 2005).

Flax, also known as linseed, is grown on the Canadian prairies. It has been estimated that Canada produces from 25 to 40% of the total global flaxseed output annually depending on climate, price, and export market (AAFC 2005). GE oilseed crops, including flax, could be used for production of a wide range of bio-products including biofuels, lubricants, plastics, healthy oils, green building materials, and pharmaceuticals (Morygonov et al. 2008). Flax is the richest plant source of α-linolenic acid, an ω-3 fatty acid, and thus the demand for flax is increasing in the functional food market (Fitzpatrick 2007). Ingestion of flax oil has been shown to reduce the risk factor of cardiovascular diseases (Bloedon and Szapary 2004). Because of the potential of flax for industrial, functional, and edible uses, it is being investigated as a platform crop for bio-products.

Conventional flax grown in Canada is marketed primarily to the EU, and the residual meal is used as a coproduct in animal feed. A transgenic flax cultivar 'CDC Triffid' was previously released in Canada (McHughen et al. 1997). This herbicide-resistant cultivar was intended for use in fields with persistent sulfonylurea herbicides residues. However, CDC Triffid was deregulated a few years after its release in 1998 at the request of the Canadian flax seed industry due to the negative market response of the EU to importing GE flaxseeds (Anonymous 2002). Further transgenic development of flax was halted as a clear regulatory framework did not exist for transgenic crops or feed products in Europe at the time of its release. At present, the European Commission (EC) is proposing and implementing measures to achieve coexistence between GE and non-GE crops (Devos et al. 2009).

The prominent crop rotation in flax-growing regions of western Canada is flax followed by cereals, usually wheat (*Triticum aestivum* L.). GE volunteer flax that set seed may be harvested with wheat. In addition to flax, Canada is also one of the largest producers and exporters of wheat (Statistics Canada 2007). In 2008, Canada exported 936 thousand tonnes of wheat seed to European countries (Canadian Grain Commission 2008). The European government, media, and public are very sensitive to products derived from recombinant DNA technology and thus have established strict regulations concerning adventitious presence (Demont et al. 2008). Production of GE flax may raise concerns about seed-

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mediated gene flow and commingling of flax seed with wheat seed when wheat is grown in rotation as a subsequent crop.

The EC currently accepts adventitious presence of authorized transgenes in organic and conventional non-GE products used for food or feed up to a 0.9% threshold level in EU-approved GE crops (Commission of the European Communities 2003). No thresholds have been established, however, for unauthorized events (Devos et al. 2005). Some countries including Canada and the United States consider GE crops substantially equivalent to conventional and organic crops and do not require GE crops to be labeled (Smyth and McHughen 2008). It is not known whether GE and conventional flax could coexist in Canada without risk to the conventional flax or wheat export market.

Crop volunteers are important weeds in western Canadian cropping systems (Leeson et al. 2005). While there is excellent research on response of crop species to management and to its receiving environment, relatively little is known about their biology as a weedy species. There has been renewed interest in the biology of crop volunteers since the introduction of GE crops (for examples see Beckie and Owen 2007, Beckie et al. 2006, Harker et al. 2007, and Warwick et al. 2009). GE crop volunteers may flower and pollinate adjacent crops, contributing to pollen-mediated gene flow (Mallory-Smith and Zapiola 2008). Volunteers of GE crops may also survive to produce seed that can recharge the weed seed bank or be harvested along with the crop grown in rotation, resulting in adventitious presence of transgenes (Beckie and Owen 2007). Seed dispersal of crops has the potential to contribute to large scale gene flow, both temporally and spatially.

Gene flow via seed from flax volunteers has the potential to significantly influence the processes that either initiate or contribute to adventitious presence. Volunteer flax initially arises from seed and capsule losses incurred during flax harvest. The relative abundance of volunteer flax has increased across western Canada over the last 30 yr. Averaged across Manitoba, Saskatchewan, and Alberta, volunteer flax ranked as the 32nd most abundant weed in the 1970s and as the 26th most abundant weed in the 1990s and early 2000s (Leeson et al. 2005). It appears that GE flax, like conventional flax, would have significant potential for volunteerism in western Canada. If flax is to be developed as a bio-industrial crop, quantifying the contribution of flax volunteers to adventitious presence in subsequent crops is necessary to determine whether the EU thresholds can be met.

Herbicidal control of volunteers is an important component of risk reduction in coexistence of GE and conventional crops (Gruber et al. 2008). In Canada, few PRE and POST herbicides have been registered for volunteer flax control in cereals (Brook 2007). Glyphosate applied PRE alone or with the acetolactate synthase (ALS) inhibitor tribenuron is registered in Canada for control of volunteer flax. POST herbicide options for control of volunteer flax include the auxin inhibitors fluroxypyr plus 2,4-D and fluroxypyr plus MCPA or quinclorac, and the ALS inhibitor tribenuron used independently or in combination with 2,4-D or quinclorac (Anonymous 2008). Quinclorac applied POST at 100 or 200 g a.i. ha^{-1} has been shown to provide consistent volunteer flax control without yield loss in spring wheat (Wall and Smith 1999). Fluroxypyr plus 2,4-D has been previously reported to be as effective as quinclorac in its ability to control volunteer flax, but flax control by fluroxypyr plus MCPA has not been evaluated in spring wheat (Wall and Smith 1999). Flax is quite tolerant to some ALS inhibitors. Thifensulfuron was examined as an herbicide for weed control in flax, but it caused injury to flax when applied POST, and reductions in flax dry weight, height, and yield—especially under cool and wet growing conditions—were reported (Derksen and Wall 1996).

Contribution of flax volunteers to adventitious presence in cereals has not yet been identified. If the risk of seed-mediated gene flow from transgenic flax volunteers in rotational cereal crops is to be mitigated, an effective combination of PRE and POST herbicides, or a single or split POST herbicide treatment(s), must be identified. Therefore, this experiment was planned based on the following objectives: (1) to compare the control of volunteer flax with PRE and POST herbicides alone or in combination in spring wheat, (2) to evaluate fecundity of volunteer flax plants in wheat in herbicide treated and untreated conditions, and (3) to quantify the potential adventitious presence of volunteer flax in wheat. Data from these experiments will inform environmental risk assessment of GE flax and contribute to an understanding of seed-mediated gene flow of flax, and may result in a strategy to mitigate adventitious presence of GE flax in cereals.

Materials and Methods

Site Information and Experimental Design. In Canada, few herbicides are registered for volunteer flax control in cereals. Field experiments were conducted to examine the use of two PRE (glyphosate, glyphosate plus tribenuron) and five POST (fluroxypyr plus 2,4-D or MCPA or quinclorac, thifensulfuron plus tribenuron or 2,4-D or quinclorac) herbicides used alone and in combination to reduce adventitious presence of flax seed in spring wheat.

Field experiments were conducted in 2005 and 2006 at two locations in central Alberta, Canada: the University of Alberta Edmonton Research Station (ERS) and the Ellerslie Research Station (Ellerslie). At the ERS, the soil was a clay loam and consisted of 31.8% sand, 40.8% silt, and 27.4% clay with a pH of 6.0 and an organic matter content of 12.2%. Soil texture at Ellerslie was a loam soil and consisted of 28.6% sand, 46.4% silt, and 25% clay with a pH of 6.3 and 11.5% soil organic matter content. In the year prior to the 2005 and 2006 research experiments, the research sites were planted to barley (cultivar [cv.] 'AC Metcalfe'), and the excess straw was removed by performing two light harrow operations before flax was planted. The experiments at both sites/years were established in areas that had not been seeded to flax and had not been tilled for at least 5 yr.

To simulate volunteer flax infestations, flax cv. 'CDC Bethune' was broadcasted on the soil surface in spring at a rate of 12.22 kg ha^{-1} with target populations of 150 seeds m^{-2} with a low disturbance airseeder.[1] This seeding rate was selected since it simulated maximum densities of volunteer flax typically observed in commercial fields. Seed was immediately incorporated into the soil with a light tillage operation to a depth of 2.5 to 4 cm (Table 1). Flax volunteers were allowed to emerge and PRE herbicides were applied. After PRE herbicide treatments, spring wheat cv. 'AC Barrie' was seeded using a double disc press drill[2] at a rate of 114 kg ha^{-1} at a depth of 3.0 cm and with a row spacing of 20 cm at all research locations (Table 1). Spring wheat seeding dates were delayed compared to those typical for the

Table 1. Dates of agronomic operations at ERS[a] and Ellerslie[a] in 2005 and 2006.

Operation	ERS		Ellerslie	
	2005	2006	2005	2006
Flax cv.[a] CDC Bethune seeded	May 6	May 10	May 4	May 11
Flax incorporation by tillage	May 6	May 10	May 4	May 11
PRE herbicide treatment applied	June 7	May 31	June 2	June 4
Spring wheat cv. AC Barrie seeded	June 3	May 29	June 3	June 5
Volunteer flax density assessments after PRE herbicide treatment	June 14	June 10	June 14	June 10
Volunteer flax density assessments at the time of harvest	Oct 6	Sept 11	Oct 6	Sept 25
POST herbicide treatments	June 28	June 20	June 28	June 26
Volunteer flax and wheat biomass assessments	Oct 6	Sept 11	Oct 6	Sept 25
Wheat harvest	Oct 10	Sept 28	Oct 10	Sept 28

[a] Abbreviations: ERS, University of Alberta Edmonton Research Station; Ellerslie, Ellerslie Research Station; cv., cultivar.

area because of the need to establish volunteer flax and apply PRE herbicides.

Fertilizer rates for wheat were based on soil test recommendations for each site/year. In 2005 and 2006 at Ellerslie, 170.24 kg ha^{-1} of urea (46–0–0) was broadcasted on the soil surface and 44.8 kg ha^{-1} of phosphate (0–45–0) was placed with seed. At the ERS in 2005, 16.0 kg ha^{-1} of potassium sulfate (0–0–52–17) and 37.0 kg ha^{-1} of urea (46–0–0) were broadcasted on the soil surface, and in 2006, 170.24 kg ha^{-1} of urea (46–0–0) and 44.8 kg ha^{-1} of phosphate (0–45–0) were broadcasted.

Plots of size 2 by 8.5 m^2 were arranged in a randomized complete block design (RCBD) with 18 treatments being randomly assigned to plots within each of four replications. The 18 treatments consisted of 2 PRE herbicide treatments, 5 POST herbicides alone, 10 PRE followed by POST herbicide treatments, and an untreated weedy control (Table 2). Prior to seeding the wheat crop, a 1 by 2-m^2 quadrat was randomly placed in each plot and was permanently established by marking each corner. PRE and POST herbicides were applied at recommended rates (Table 2) and stages of crop development. PRE herbicides were applied when volunteer flax was 6 to 8 cm tall with the third pair of leaves unfolded, and POST herbicides were applied when the wheat crop was at the five- to six-leaf stage and volunteer flax was $\geq$ 15 cm tall. Herbicides were applied with a small plot-sprayer[3] equipped with shrouded multiple 2-m booms equipped with Teejet XR 110015 nozzles[4] delivering 100 L ha^{-1} at 214 kPa.

Volunteer flax density within preestablished 1 by 2-m^2 quadrats was assessed during the growing season: (1) prior to herbicide treatment, (2) 2 wk after PRE herbicide treatment, and (3) at the time of harvest (Table 1). Volunteer flax that survived after herbicide treatments were cut at the stem base close to the soil surface, dried for 48 h at room temperature (25 C) and the dry weights (g) were recorded. A drying temperature of 25 C was used so seeds could be tested for viability. Flax seed capsules were threshed by hand, and seeds were tested for viability (see below). Wheat biomass was also determined (Table 1) in preestablished 1 by 2-m^2 quadrats by cutting the plants off at the stem base near the soil surface, drying for 72 h at 62 C, and weighing (g). Plots were harvested at maturity (Table 1) and the admixture of seeds was dried to uniform moisture content for 72 h at 62 C. Samples were cleaned, volunteer flax seeds were separated, and wheat yield (kg ha^{-1}) was recorded. Adventitious presence of volunteer flax was determined by recovering volunteer flax seeds from the harvested wheat samples. The adventitious presence of volunteer flax in spring wheat (kg ha^{-1}) was determined by weighing the recovered seed (g) and expressing it as a percentage (g/g) using the following formula:

$$\text{Volunteer flax adventitious presence } (\%) = Yf / Yw \times 100 \quad [1]$$

where adventitious presence is the adventitious presence of volunteer flax in wheat expressed as a percent, *Yf* is the weight of flax seeds (g), and *Yw* is the weight of wheat seeds (g).

Volunteer Flax Seed Viability Test. In preliminary experiments (n = 8,800), an average of 86.7% of seed (variety CDC Bethune) germinated at room temperature in water, and an additional 2.1% of seed germinated after the addition of gibberellic acid (GA_3). Of the remaining nongerminated seeds, an average of 1.5% were viable when tested with tetrazolium and 9.4% were nonviable, including soft/degrading seed. Small seed size prohibited the use of tetrazolium testing on all seeds. We concluded that seeds that germinated following GA_3 treatment were viable and considered nongerminated seeds as nonviable, accepting an average error rate of 1.5%.

To determine volunteer flax seed viability, a subsample of 100 seeds from each sample of harvested flax volunteers was randomly chosen after sample processing. Seeds were placed in acrylic germination boxes[5] (24 by 16 by 3.8 cm) lined with 15 by 23-cm nontoxic white filter paper[6] equivalent to Whatman No. 1. To reduce fungal growth, 14 mL of a 0.2% solution of the seed treatment Helix Xtra[7] was added to each germination box. Germination trays were stored in the dark at ambient temperatures for 72 h to induce germination. Seeds were considered to have germinated when the radicle emerged through the seed coat. Nonviable seeds were soft and degraded and covered in a mucous-like film.

Nongerminated seeds were transferred to acrylic germination boxes (24 by 16 by 3.8 cm) lined with 15 by 23-cm nontoxic white filter paper equivalent to Whatman No. 1, and moistened with 8 ml of 0.005 M GA_3[8] solution. Turgid seeds were classified as nongerminated. After 72 h on the 0.005 M GA_3 solution, the number of flax seeds that did and did not germinate were counted and recorded. Germinated seeds were considered to be viable and nongerminated seeds were considered to be nonviable.

Statistical Analysis. Data were subjected to ANOVA within a mixed model (PROC MIXED) using SAS.[9] The assumptions of random, homogenous residuals with a normal distribution were checked to ensure the validity of ANOVA. Where required, variables were log transformed to allow for conformity and back-transformed means were presented. Volunteer flax emergence, density after herbicide treatment,

Table 2. PRE and POST herbicides, adjuvants, and application rates used in this experiment.

Treatment	PRE	POST	PRE rate	POST rate
1	—[a]	—	—	0
2	Glyphosate[10]	—	1.25 L ha^{-1}	0
3	Tribenuron[11]	—	7.41 g a.i. ha^{-1}	0
	Glyphosate		0.98 L ha^{-1}	
	AgSurf[12]		0.2% v/v	
4	—	Thifensulfuron[13] + tribenuron	—	14.82 g a.i. ha^{-1}
		AgSurf		0.2% v/v
5	—	Fluroxypyr[14]	—	0.59 L ha^{-1}
		MCPA[15]		0.98 L ha^{-1}
6	—	Fluroxypyr	—	0.59 L ha^{-1}
		2,4-D[16]		1.11 L ha^{-1}
7	—	Thifensulfuron + tribenuron	—	14.82 g a.i ha^{-1}
		2,4-D		0.90 L ha^{-1}
		AgSurf		0.2% v/v
8	—	Thifensulfuron + tribenuron	—	14.82 g a.i ha^{-1}
		Quinclorac[17]		124.12 g a.i ha^{-1}
		Merge[18]		0.2% v/v
9	Glyphosate	Thifensulfuron + tribenuron	1.25 L ha^{-1}	14.82 g a.i. ha^{-1}
		AgSurf		0.2% v/v
10	Glyphosate	Fluroxypyr	1.25 L ha^{-1}	0.59 L ha^{-1}
		MCPA		0.98 L ha^{-1}
11	Glyphosate	Fluroxypyr	1.25 L ha^{-1}	0.59 L ha^{-1}
		2,4-D		1.11 L ha^{-1}
12	Glyphosate	Thifensulfuron + tribenuron	1.25 L ha^{-1}	14.82 g a.i ha^{-1}
		2,4-D		0.90 L ha^{-1}
		AgSurf		0.2% v/v
13	Glyphosate	Thifensulfuron + tribenuron	1.25 L ha^{-1}	14.82 g a.i ha^{-1}
		Quinclorac		124.12 g a.i ha^{-1}
		Merge		0.2% v/v
14	Tribenuron + Glyphosate	Thifensulfuron + tribenuron	7.41 g a.i. ha^{-1}	14.82 g a.i. ha^{-1}
	AgSurf		0.98 L ha^{-1}	
		AgSurf	0.2% v/v	0.2% v/v
15	Tribenuron	Fluroxypyr	7.41 g a.i. ha^{-1}	0.59 L ha^{-1}
	Glyphosate	MCPA	0.98 L ha^{-1}	0.98 L ha^{-1}
	AgSurf		0.2% v/v	
16	Tribenuron	Fluroxypyr	7.41 g a.i. ha^{-1}	0.59 L ha^{-1}
	Glyphosate	2,4-D	0.98 L ha^{-1}	1.11 L ha^{-1}
	AgSurf		0.2% v/v	
17	Tribenuron	Thifensulfuron + tribenuron	7.41 g a.i. ha^{-1}	14.82 g a.i ha^{-1}
	Glyphosate		0.98 L ha^{-1}	
	AgSurf	2,4-D	0.2% v/v	0.90 L ha^{-1}
		AgSurf		0.2% v/v
18	Tribenuron	Thifensulfuron + tribenuron	7.41 g a.i. ha^{-1}	14.82 g a.i ha^{-1}
	Glyphosate		0.98 L ha^{-1}	
	AgSurf	Quinclorac	0.2% v/v	124.12 g a.i ha^{-1}
		Merge		0.2% v/v

[a] —, None.

dry weight, fecundity (seed yield and seed number m^{-2}), adventitious presence, as well as wheat dry weight (biomass) (g m^{-2}) and yield (kg ha^{-1}) were analyzed using ANOVA within a 2 by 5 factorial in SAS. Factor one was PRE herbicide treatment, and factor two was POST herbicide treatment. Site and treatment effects were considered to be fixed. Year and block effects were considered to be random. Where the ANOVA indicated that treatment effects were significant, least square means were separated at $P \leq 0.05$ with Fisher's Protected LSD test. When the effect of site, year, and their interactions with treatments were nonsignificant, data were pooled by site and year. Orthogonal contrasts were performed as part of the ANOVA procedure. Specific contrasts tested included untreated vs. PRE; untreated vs. POST; glyphosate vs. glyphosate + tribenuron; thifensulfuron + tribenuron vs. thifensulfuron + tribenuron + 2,4-D; thifensulfuron + tribenuron vs. thifensulfuron + tribenuron + quinclorac; thifensulfuron + tribenuron vs. fluroxypyr + MCPA; thifensulfuron + tribenuron vs. fluroxypyr + 2,4-D; fluroxypyr + MCPA vs. fluroxypyr + 2,4-D; glyphosate vs. PRE × POST and glyphosate + tribenuron vs. PRE × POST. Differences were considered to be significant when $P \leq 0.05$.

Results and Discussion

The preservation of market value of spring wheat and conventional flax must be considered prior to the introduction of new GE crops. From the perspective of the grower, effective control of volunteer flax increased wheat yield, reduced harvest difficulties from fibrous volunteers, blocked replenishment of the seed bank, and reduced subsequent volunteer populations. Effective volunteer control reduced potential pollen-mediated gene flow to adjacent flax fields, seed mediated gene flow through decreased seed viability, and amount of adventitious presence of flax seed in wheat crops.

Volunteer flax density and dry weight did not differ among sites ($0.089 < P < 0.313$) or years ($0.228 < P < 0.404$) and therefore sites were analyzed together (Table 3). Both PRE treatments of glyphosate or glyphosate plus tribenuron

Table 3. Volunteer flax density and dry weight from fixed quadrats as influenced by herbicide treatments at ERS[a] and Ellerslie,[a] Alberta, in 2005 and 2006.

Treatment	Application timing	Density after PRE herbicide application[b]	Density at harvest[b]	Dry weight[b]
		plants m^{-2}		$g\ m^{-2}$
Untreated	—	41 ab	39 a	109 a
Glyphosate	PRE	7 cd	4 d	9 d
Glyphosate + tribenuron	PRE	5 d	6 d	19 cd
Thifensulfuron + tribenuron	POST	38 b	36 ab	82 ab
Fluroxypyr + MCPA	POST	36 b	4 d	5 d
Fluroxypyr + 2,4-D	POST	36 b	2 d	3 d
Thifensulfuron + tribenuron + 2,4-D	POST	45 a	27 bc	70 b
Thifensulfuron + tribenuron + quinclorac	POST	43 ab	21 c	54 bc
Glyphosate *fb*[a] thifensulfuron + tribenuron	PRE/POST	14 c	7 d	10 d
Glyphosate *fb* fluroxypyr + MCPA	PRE/POST	8 cd	1 d	3 d
Glyphosate *fb* fluroxypyr + 2,4-D	PRE/POST	6 d	0 d	1 d
Glyphosate *fb* thifensulfuron + tribenuron + 2,4-D	PRE/POST	6 cd	2 d	5 d
Glyphosate *fb* thifensulfuron + tribenuron + quinclorac	PRE/POST	6 cd	1 d	2 d
Glyphosate + tribenuron *fb* thifensulfuron + tribenuron	PRE/POST	7 cd	5 d	7 d
Glyphosate + tribenuron *fb* fluroxypyr	PRE/POST	5 d	0 d	0 d
Glyphosate + tribenuron *fb* fluroxypyr + 2,4-D	PRE/POST	7 cd	1 d	1 d
Glyphosate + tribenuron *fb* thifensulfuron + tribenuron + 2,4-D	PRE/POST	7 cd	2 d	3 d
Glyphosate + tribenuron *fb* thifensulfuron + tribenuron + quinclorac	PRE/POST	6 d	6 d	13 cd
Sources of variation[c]				
PRE herbicides		*	*	*
POST herbicides		**NA**[a]	*	*
PRE herbicides × POST herbicides		**NA**[a]	*	*

[a] Abbreviations: ERS, University of Alberta Edmonton Research Station; Ellerslie, Ellerslie Research Station; fb, followed-by; NA, not applicable.
[b] Least square means within columns followed by a common letter are not significantly different according to Fischer's Protected LSD test at $P \leq 0.05$. Counts were recorded 2 wk after herbicide application.
[c] Nonorthogonal contrasts denoted by an asterisk (*) are significant at $P \leq 0.05$.

reduced volunteer flax densities from 41 plants m^{-2} to 7 and 5 plants m^{-2}, respectively, 2 wk after treatment. Similarly at harvest, average densities of volunteer flax were lower in plots that received PRE glyphosate or glyphosate plus tribenuron (4 and 6 plants m^{-2}, respectively) compared to untreated controls (39 plants m^{-2}). Volunteer flax dry weight was similarly reduced by both PRE herbicide treatments. Dry weights of volunteer flax plants treated with glyphosate or glyphosate plus tribenuron averaged 9 and 19 g m^{-2}, respectively, whereas the untreated weedy control averaged 109 g m^{-2}. There were no differences in volunteer flax densities and dry weights between the two PRE herbicide treatments applied alone (without POST herbicides).

POST treatment of thifensulfuron plus tribenuron was ineffective at reducing the density of volunteer flax at harvest (36 plants m^{-2}) and was also ineffective in reducing volunteer flax dry weight (82 g m^{-2}) compared to the untreated weedy control (39 plants m^{-2} and 109 g m^{-2}) (Table 3). These results were consistent with those of Wall and Smith (1999), who reported that thifensulfuron plus tribenuron applied POST provided poor control of volunteer flax in spring wheat. They reported that volunteer flax densities in untreated weedy plots (344 to 476 plants m^{-2}) were similar to densities of volunteer flax following thifensulfuron plus tribenuron (325 to 476 plants m^{-2}).

In this study, the addition of either 2,4-D or quinclorac to thifensulfuron plus tribenuron applied POST reduced volunteer flax density and dry weight at harvest (Table 3). Compared to the untreated weedy control, thifensulfuron plus tribenuron applied POST with either 2,4-D or quinclorac reduced volunteer flax densities at harvest from 39 plants m^{-2} to 27 and 21 plants m^{-2}, respectively. Volunteer flax dry weight was also reduced by POST thifensulfuron plus tribenuron plus 2,4-D (70 g m^{-2}) or quinclorac (54 g m^{-2}) compared to the untreated weedy plots (109 g m^{-2}). These results contrast with those of Wall and Smith (1999), who reported that the addition of 2,4-D to thifensulfuron plus tribenuron provided ineffective control of volunteer flax (density and dry weight) compared to the untreated weedy control.

Fluroxypyr plus MCPA and fluroxypyr plus 2,4-D were the most effective POST treatments for reducing density and dry weight of volunteer flax in spring wheat (Table 3). Compared to the untreated weedy control, they reduced volunteer flax densities at harvest from 39 plants m^{-2} to 4 and 2 plants m^{-2}, respectively. Volunteer flax dry weight was 5 and 3 g m^{-2}, respectively, in plots treated with either fluroxypyr plus MCPA or fluroxypyr plus 2,4-D, compared to that in untreated plots (109 g m^{-2}). Fluroxypyr plus 2,4-D applied POST in spring wheat was previously reported to reduce volunteer flax density and dry weight up to 3 and 80 times, respectively, in comparison to untreated plots in Manitoba (Wall and Smith 1999).

In this study, both PRE herbicides (glyphosate or glyphosate plus tribenuron) were as effective as some POST herbicides (fluroxypyr plus MCPA and fluroxypyr plus 2,4-

Table 4. Wheat biomass (g m^{-2}) and yield (kg ha^{-1}) as influenced by PRE herbicides, POST herbicides, or their combinations at ERS[a] and Ellerslie.[a]

Treatment	Application timing	Wheat biomass[b]		Wheat seed yield[b]
		ERS	Ellerslie	
		g m^{-2}		kg ha^{-1}
Untreated	—	311	744	1,079
Glyphosate	PRE	751	838	1,807
Glyphosate + tribenuron	PRE	663	873	1,666
Thifensulfuron + tribenuron	POST	465	749	1,364
Fluroxypyr + MCPA	POST	614	697	1,515
Fluroxypyr + 2,4-D	POST	523	636	1,390
Thifensulfuron + tribenuron + 2,4-D	POST	506	594	1,309
Thifensulfuron + tribenuron + quinclorac	POST	521	705	1,469
Glyphosate *fb*[a] thifensulfuron + tribenuron	PRE/POST	594	863	1,695
Glyphosate *fb* fluroxypyr + MCPA	PRE/POST	666	886	1,831
Glyphosate *fb* fluroxypyr + 2,4-D	PRE/POST	690	974	1,815
Glyphosate *fb* thifensulfuron + tribenuron + 2,4-D	PRE/POST	691	940	1,852
Glyphosate *fb* thifensulfuron + tribenuron + quinclorac	PRE/POST	675	961	1,793
Glyphosate + tribenuron *fb* thifensulfuron + tribenuron	PRE/POST	648	904	1,816
Glyphosate + tribenuron *fb* fluroxypyr	PRE/POST	678	885	1,899
Glyphosate + tribenuron *fb* fluroxypyr + 2,4-D	PRE/POST	655	926	1,771
Glyphosate + tribenuron *fb* thifensulfuron + tribenuron + 2,4-D	PRE/POST	686	870	1,749
Glyphosate + tribenuron *fb* thifensulfuron + tribenuron + quinclorac	PRE/POST	744	975	1,847
Contrast statements[c]				
Untreated vs. PRE		*	**NS**	*
Untreated vs. POST		*	**NS**	*
Glyphosate vs. glyphosate + tribenuron		**NS**	**NS**	**NS**
Thifensulfuron + tribenuron vs. thifensulfuron + tribenuron + 2,4-D		**NS**	**NS**	**NS**
Thifensulfuron + tribenuron vs. thifensulfuron + tribenuron + quinclorac		**NS**	**NS**	**NS**
Thifensulfuron + tribenuron vs. fluroxypyr + MCPA		**NS**	**NS**	**NS**
Thifensulfuron + tribenuron vs. fluroxypyr + 2,4-D		**NS**	**NS**	**NS**
Fluroxypyr + MCPA vs. fluroxypyr + 2,4-D		**NS**	**NS**	**NS**
Glyphosate vs. PRE × POST		**NS**	**NS**	**NS**
Glyphosate + tribenuron vs. PRE × POST		**NS**	**NS**	**NS**

[a] Abbreviations: ERS, University of Alberta Edmonton Research Station; Ellerslie, Ellerslie Research Station; *fb*, followed-by.
[b] Least square means from the mixed model ANOVA.
[c] Nonorthogonal contrasts denoted by an asterisk (*) are significant at $P \leq 0.05$ and those denoted by NS are not significant at $P \leq 0.05$.

D) in reducing the density and dry weight of volunteer flax at harvest (Table 3). In addition, there were no differences in the density and dry weight of volunteer flax when plots were treated with PRE glyphosate (4 plants m^{-2} and 9 g m^{-2}) or glyphosate plus tribenuron (6 plants m^{-2} and 19 g m^{-2}); or with either POST fluroxypyr plus MCPA (4 plants m^{-2} and 5 g m^{-2}) or fluroxypyr plus 2,4-D (2 plants m^{-2} and 3 g m^{-2}) or when plots were treated in combination with either of these PRE followed by POST herbicides (Table 3). These results suggest that a combination of both treatments (PRE and POST) was not necessary. Results, however, must be viewed with caution. To ensure uniform populations, flax was seeded and emerged prior to PRE herbicides and before seeding the wheat crop. Under agronomic conditions, volunteer flax continues to emerge after preseeding herbicides, and thus PRE products may have reduced effectiveness.

Crop Response. Wheat biomass differed between sites ($P = 0.011$) but wheat yield did not differ as a result of a site by year interaction ($P = 0.345$) (Table 4). Wheat biomass was increased by all herbicide treatments at ERS, but not at Ellerslie. The maximum wheat biomass (751 g m^{-2}) was recorded when only glyphosate was applied PRE at ERS, more than double the untreated control (311 g m^{-2}). At Ellerslie, the maximum wheat biomass was 975 g m^{-2} (Table 4), but there were no significant differences between treatments.

Differences in wheat yield among treatments generally reflected the level of volunteer flax control. All herbicide treatments increased wheat yields in all sites/years. This included the POST thifensulfuron plus tribenuron treatment, which was ineffective at controlling flax volunteers, suggesting that the yield increases were due, at least in part, to the control of other weeds. In untreated plots, in addition to volunteer flax, other weed species including common lambsquarters, (*Chenopodium album* L.), redroot pigweed (*Amaranthus retroflexus* L.) and volunteer barley (*Hordeum vulgare* L.) were present. In plots treated with either only PRE or POST herbicides, wheat yields ranged from 1,309 to 1,807 kg ha^{-1}, whereas in untreated plots, wheat yield averaged 1,079 kg ha^{-1}. There were no differences in wheat yields between PRE, POST, or additive herbicide treatments ($0.188 < P < 0.932$) between the two sites. Maximum wheat yield (1,899 kg ha^{-1}) was recorded when PRE glyphosate was followed by POST tribenuron plus fluroxypyr, but it was similar to other herbicide treatments.

Previous research has indicated that when volunteer flax was left uncontrolled and present at high average densities (105 plants m^{-2}), spring wheat yields may be reduced by 27% in western Canada (Wall and Smith 1999). Although the densities of volunteer flax did not exceed 41 plants m^{-2} in this study (Table 3), wheat yields were reduced by up to 57% in untreated plots. Delayed crop seeding likely increased the potential for yield loss by changing the relative competitiveness of the flax volunteers and wheat.

Table 5. Volunteer flax seed production from fixed quadrats as influenced by herbicide treatments at ERS[a] and Ellerslie,[a] Alberta in 2005 and 2006.

Treatment	Application timing	Volunteer flax seed production[b]				
		ERS	Ellerslie	ERS	Ellerslie	Viable seed
		g m^{-2}		seeds m^{-2}		%
Untreated	—	3.1	30.9	483.2	4,755.3	55.5
Glyphosate	PRE	0.4	0.8	55.6	121.8	39.9
Glyphosate + tribenuron	PRE	0.4	7.7	57	1,187.4	36.9
Thifensulfuron + tribenuron	POST	4.1	4.2	626.1	650.5	46.8
Fluroxypyr + MCPA	POST	0.0	0.1	0.6	11.4	10
Fluroxypyr + 2,4-D	POST	0.0	0.0	2.1	0.0	3.8
Thifensulfuron + tribenuron + 2,4-D	POST	1.2	8.7	184.4	1,342.7	45.2
Thifensulfuron + tribenuron + quinclorac	POST	1.2	4.4	177	680	33.2
Glyphosate *fb*[a] thifensulfuron + tribenuron	PRE/POST	0.4	0.1	65.5	17.3	17.3
Glyphosate *fb* fluroxypyr + MCPA	PRE/POST	0.0	0.0	0.0	5.3	4
Glyphosate *fb* fluroxypyr + 2,4-D	PRE/POST	0.0	0.0	0.0	0.0	0.0
Glyphosate *fb* thifensulfuron + tribenuron + 2,4-D	PRE/POST	0.1	0.0	15.7	6.1	5
Glyphosate *fb* thifensulfuron + tribenuron + quinclorac	PRE/POST	0.1	0.0	7.1	0.0	5
Glyphosate + tribenuron *fb* thifensulfuron + tribenuron	PRE/POST	0.2	0.8	29.8	115	12.4
Glyphosate + tribenuron *fb* fluroxypyr	PRE/POST	0.0	0.0	0.0	0.0	0.0
Glyphosate + tribenuron *fb* fluroxypyr + 2,4-D	PRE/POST	0.0	0.0	0.0	3.1	1.4
Glyphosate + tribenuron *fb* thifensulfuron + tribenuron + 2,4-D	PRE/POST	0.1	0.1	11	15.7	9
Glyphosate + tribenuron *fb* thifensulfuron + tribenuron + quinclorac	PRE/POST	0.5	0.0	78.3	3	10
Contrast statements[c]						
Untreated vs. PRE		*	*	*	*	**NS**
Untreated vs. POST		*	*	*	*	*
Glyphosate vs. glyphosate + tribenuron		**NS**	**NS**	**NS**	**NS**	**NS**
Thifensulfuron + tribenuron vs. thifensulfuron + tribenuron + 2,4-D		*	**NS**	*	**NS**	*
Thifensulfuron + tribenuron vs. thifensulfuron + tribenuron + quinclorac		*	**NS**	*	**NS**	*
Fluroxypyr + MCPA vs. fluroxypyr + 2,4-D		**NS**	**NS**	**NS**	**NS**	**NS**
Glyphosate vs. PRE × POST		**NS**	**NS**	**NS**	**NS**	*
Glyphosate + tribenuron vs. PRE × POST		**NS**	**NS**	**NS**	**NS**	*

[a] Abbreviations: ERS, University of Alberta Edmonton Research Station; Ellerslie, Ellerslie Research Station; *fb*, followed by.
[b] Least square means from the mixed model ANOVA.
[c] Nonorthogonal contrasts denoted by an asterisk (*) are significant at $P \leq 0.05$ and those denoted by NS are not significant at $P \leq 0.05$.

Volunteer Flax Seed Production, Adventitious Presence, and Viability. Volunteer flax, if left uncontrolled, can produce large amounts of seeds (Table 5). Seed production of untreated flax volunteers differed between sites ($P = 0.008$), ranging from 3.1 to 30.9 g m^{-2} or from 483 to 4,755 seeds m^{-2} at ERS and Ellerslie, respectively (Table 5). There were no differences in precipitation among sites/years that would explain greater seed production of volunteer flax at Ellerslie compared to ERS (data not shown). Higher volunteer flax seed yields at Ellerslie than at ERS, however, reflected site quality differences.

Both PRE and most POST herbicide treatments reduced seed production of volunteer flax ($0.000 < P < 0.007$) (Table 5). Compared to the untreated weedy plots, both PRE treatments of glyphosate or glyphosate plus tribenuron reduced the flax seed production at both sites by 75% or more. There were no differences in volunteer flax seed production between two PRE herbicide treatments at either site (Table 5). In addition, there were no differences in seed production when PRE glyphosate was used alone compared to the addition of a POST herbicide treatment. Flax seed production was also decreased by POST thifensulfuron plus tribenuron with 2,4-D (1.2 to 8.7 g m^{-2}) or quinclorac (1.2 to 4.4 g m^{-2}) compared to the untreated control (3.1 to 30.9 g m^{-2}) (Table 5). POST treatments of fluroxypyr plus 2,4-D or fluroxypyr plus MCPA were most effective in reducing volunteer flax seed production among all the POST herbicide treatments when applied alone. Compared to the untreated controls, these POST herbicide treatments reduced the volunteer flax seed production from 4,755 to < 12 seeds m^{-2} (Table 5).

Differences in flax seed production among POST herbicide treatments were detected at ERS, but not at Ellerslie. At ERS, thifensulfuron plus tribenuron and thifensulfuron plus tribenuron with 2,4-D or quinclorac applied POST were not as effective as POST fluroxypyr plus 2,4-D or fluroxypyr plus MCPA in reducing the seed production of volunteer flax. The variance observed in flax seed production was higher at Ellerslie than ERS (data not shown), and our ability to make comparisons and to detect significant differences among POST herbicide treatments at Ellerslie may have been limited by the variance in relation to the mean.

Volunteer flax seed yields (kg ha^{-1}) and adventitious presence (%) in spring wheat differed between sites ($P = 0.000$) (Table 6). In untreated plots, yield of volunteer flax seed averaged 4.4 and 134.9 kg ha^{-2} in ERS and Ellerslie, respectively (Table 6). Compared to the untreated control, both PRE herbicide treatments (glyphosate or glyphosate plus tribenuron) and fluroxypyr plus MCPA or fluroxypyr plus 2,4-D applied POST reduced adventitious presence to 0.2% (g/g) or lower at both sites. The addition of a POST herbicide treatment after a PRE herbicide treatment of either glyphosate or glyphosate plus tribenuron did not reduce the adventitious presence of seed from flax volunteers; however, lower flax yields (≤ 0.08 kg ha^{-1}) and adventitious presence (0.0%) were recorded when fluroxypyr plus 2,4-D was applied POST after a PRE glyphosate (Table 6). Sequential application of PRE and POST herbicide did not reduce fecundity or adventitious presence under these experimental conditions but may reduce the risk of volunteer flax adventitious presence in wheat under more agronomically realistic conditions.

Table 6. Volunteer flax seed yield (kg ha^{-1}) and Adventitious Presence (%) in spring wheat from harvested plots as influenced by herbicide treatments at ERS[a] and Ellerslie,[a] Alberta in 2005 and 2006.

Treatment	Application timing	Adventitious presence[b]			
		ERS	Ellerslie	ERS	Ellerslie
		kg ha^{-1}		%	
Untreated	—	4.4	134.9	0.6	8.6
Glyphosate	PRE	0.3	4.7	0.0	0.2
Glyphosate + tribenuron	PRE	0.6	25	0.1	0.1
Thifensulfuron + tribenuron	POST	4.4	11.8	0.5	0.6
Fluroxypyr + MCPA	POST	0.1	0.5	0.0	0.0
Fluroxypyr + 2,4-D	POST	0.4	0.4	0.0	0.1
Thifensulfuron + tribenuron + 2,4-D	POST	1.5	24.8	0.2	1.5
Thifensulfuron + tribenuron + quinclorac	POST	1.7	7.7	0.1	0.4
Glyphosate *fb* thifensulfuron + tribenuron	PRE/POST	0.3	0.2	0.1	0.0
Glyphosate *fb* fluroxypyr + MCPA	PRE/POST	0.1	0.3	0.0	0.0
Glyphosate *fb* fluroxypyr + 2,4-D	PRE/POST	0.0	0.1	0.0	0.0
Glyphosate *fb* thifensulfuron + tribenuron + 2,4-D	PRE/POST	0.2	0.1	0.0	0.0
Glyphosate *fb* thifensulfuron + tribenuron + quinclorac	PRE/POST	0.1	0.0	0.0	0.0
Glyphosate + tribenuron *fb* thifensulfuron + tribenuron	PRE/POST	0.3	0.5	0.0	0.0
Glyphosate + tribenuron *fb* fluroxypyr	PRE/POST	0.0	0.4	0.0	0.0
Glyphosate + tribenuron *fb* fluroxypyr + 2,4-D	PRE/POST	0.0	0.2	0.0	0.0
Glyphosate + tribenuron *fb* thifensulfuron + tribenuron + 2,4-D	PRE/POST	0.1	1.6	0.0	0.1
Glyphosate + tribenuron *fb* thifensulfuron + tribenuron + quinclorac	PRE/POST	0.1	0.2	0.0	0.0
Contrast statements[c]					
Untreated vs. PRE		*	*	**	**
Untreated vs. POST		*	*	**	**
Glyphosate vs. glyphosate + tribenuron		**NS**	**NS**	**NS**	**NS**
Thifensulfuron + tribenuron vs. thifensulfuron + tribenuron + 2,4-D		*	**NS**	**	**NS**
Thifensulfuron + tribenuron vs. thifensulfuron + tribenuron + quinclorac		*	**NS**	**	**NS**
Thifensulfuron + tribenuron vs. fluroxypyr + MCPA		*	**NS**	**	**NS**
Thifensulfuron + tribenuron vs. fluroxypyr + 2,4-D		*	**NS**	**	**NS**
Fluroxypyr + MCPA vs. fluroxypyr + 2,4-D		**NS**	**NS**	**NS**	**NS**
Glyphosate vs. PRE × POST		**NS**	**NS**	**NS**	**NS**
Glyphosate + tribenuron vs. PRE × POST		**NS**	**NS**	**NS**	**NS**

[a] Abbreviations: ERS, University of Alberta Edmonton Research Station; Ellerslie, Ellerslie Research Station; *fb*, followed-by.
[b] Least square means from the mixed model ANOVA.
[c] Nonorthogonal contrasts denoted by an asterisk (*) are significant at $P \leq 0.05$ and those denoted by NS are not significant at $P \leq 0.05$.

Plants that survive and set seed after herbicide treatment may produce seeds with decreased viability, either through a delay in seed maturity or directly (Azlin and McWhorter 1981, Cathey and Barry 1997). In untreated weedy plots, the viability of volunteer flax seed averaged 55% (Table 5). Compared to the untreated weedy plots, the percentage of viable seeds was not reduced by either PRE herbicide treatment (glyphosate or glyphosate plus tribenuron). The viability of volunteer flax seed, however, was reduced by all POST herbicide treatments and was reduced to as low as zero when glyphosate or glyphosate plus tribenuron was applied PRE and followed by POST fluroxypyr plus MCPA or 2,4-D. While these data suggest that plots treated by herbicides are not as likely to produce viable seedlings and are therefore unlikely to contribute to gene flow in the environment, some of these seeds may be harvested along with the crop and contribute to the adventitious presence. Nonviable GE flax seeds will contain transgenes that may be detected in wheat grain shipments.

Crop seeds are a common contaminant of grain. GM seeds containing approved GE traits in conventional seed of the same crop can trigger GM labeling above certain thresholds in some countries, while unapproved events are not acceptable at any level and trigger crop rejection. Detection methods to identify transgene DNA sequences are sensitive, and crop testing is now common (Demeke et al. 2006). Clarification and international harmonization of standards, along with development of mitigation methods for adventitious presence (Table 6), are critical to prevent the disruption of grain trade.

Experimental conditions in which flax was seeded prior to wheat represent a worst-case scenario, in which competitive ability and fecundity of flax would be maximized and control of advanced flax plants by POST treatments reduced. Although our data do not suggest that both PRE herbicides followed by POST contribute to flax control and reduction of fecundity, under field conditions where volunteer flax emergence is less uniform and may continue throughout the crop season, sequential treatments may be beneficial.

While adventitious presence of seed from GE crop volunteers can be minimized through best management practices and channeled production systems, it cannot be eliminated entirely (Devos et al. 2004; Gruber et al. 2008). The adventitious presence of GE flax seed in organic flax and other commodity crops is affected by volunteer density, crop competitiveness, and harvest efficiency, as well as by herbicide effectiveness. Best management practices including maintaining isolation distances, cleaning farm equipment, educating farmers, and utilizing separate supply chains for organic and transgenic crops are additional strategies to minimize the dissemination of transgenes.

Sources of Materials

[1,2] Airseeder and double disc press drill, Fabro Enterprises Ltd., 2545, North Service, Rd (W), Swift Current, Saskatchewan, S9H 5L3, Canada.

[3] Plot Sprayer, West Texas Lee, Co., Idalou, TX, USA. Available at www.westtexaslee.com.

[4] Teejet XR nozzles, Max-Quip, 11423-163 Street, Edmonton, Alberta T5M 3Y3, Canada.

[5,6] Germination boxes and filter paper, Hoffman Manufacturing, Inc, 16541 Green Bridge Road, Jefferson, OR 97352-9201, USA.

[7] Helix XTra™, Insecticide with fungicides (thiamethoxam, difenoconazole, mefenoxam, fludioxonil), Syngenta Crop Protection Canada, Inc. Suite 300, 6700 Macleod Trail South, Calgary, Alberta, T2H 0L3, Canada.

[8] Gibberellic acid, SiGEa-Aldrich Corp., P.O. Box 14508, St. Louis, MO 63178, USA.

[9] SAS 2007, The SAS systems for windows, SAS Institute Inc., P.O. Box 8000, Cary, NC 27512, USA.

[10] Glyphosate, Weathermax®, herbicide, Monsanto Canada, 900 - One Research Road, Winnipeg, Manitoba R3T 6E3, Canada.

[11] Tribenuron, E. I. Du Pont Canada, Box 2300, Streetsville, Mississauga, ON, L5M 2J4, Canada.

[12] AgSurf, nonionic surfactant, Nufarm Agriculture Inc. 5507 - 1st Street SE, Calgary, Alberta, T2H 1H9, Canada.

[13] Thifensulfuron, E. I. Du Pont Canada, Box 2300, Streetsville, Mississauga, ON, L5M 2J4, Canada.

[14] Fluroxypyr, Dow AgroSciences Canada Inc. 2100- 450 1 ST SW, Calgary, AB, T2P 5H1, Canada.

[15] MCPA, herbicide, Dow AgroSciences Canada Inc. 2100- 450 1 ST SW, Calgary, AB, T2P 5H1, Canada.

[16] 2,4-D, 2-Ethylhexyl Easter, herbicide, Dow AgroSciences Canada Inc. 2100- 450 1 ST SW, Calgary, AB, T2P 5H1, Canada.

[17] Quinclorac, herbicide, BASF, 100 Milverton Drive, 5th Floor, Mississauga, ON L5R 4H1, Canada.

[18] Merge®, surfactant blend + solvent (petroleum hydrocarbons), BASF Canada, 100 Milverton Drive, Mississauga, ON L5R 4H1, Canada.

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