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Control of Volunteer Glyphosate-Resistant Canola in Glyphosate-Resistant Sugar Beet

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Occurrence of glyphosate-resistant (GR) canola volunteers in GR sugar beet is a management concern for growers in the Northern Great Plains. Field experiments were conducted at the Southern Agricultural Research Center near Huntley, MT, in 2011 and 2012 to evaluate effective herbicide programs to control volunteer GR canola in GR sugar beet. Single POST application of triflusulfuron methyl alone at the two-leaf stage of sugar beet was more effective at 35 compared with 17.5 g ai ha^{-1}. However, rate differences were not evident when triflusulfuron methyl was applied as a sequential POST (two-leaf followed by [fb] six-leaf stage of sugar beet) program (17.5 fb 17.5 or 35 fb 35 g ha^{-1}). Volunteer GR canola plants in the sequential POST triflusulfuron methyl–containing treatments produced little biomass (11 to 15% of nontreated plots) but a significant amount of seeds (160 to 661 seeds m^{-2}). Ethofumesate (4,200 g ai ha^{-1}) PRE followed by sequential POST triflusulfuron methyl (17.5 or 35 g ha^{-1}) provided effective control (94 to 98% at 30 d after treatment [DAT]), biomass reduction (97%), and seed prevention of volunteer GR canola. There was no additional advantage of adding either desmedipham + phenmedipham + ethofumesate premix (44.7 g ha^{-1}) or ethofumesate (140 g ha^{-1}) to the sequential POST triflusulfuron methyl–only treatments. The sequential POST ethofumesate-only (140 fb 140 g ha^{-1}) treatment provided poor volunteer GR canola control at 30 DAT, and the noncontrolled plants produced 6,361 seeds m^{-2}, which was comparable to the nontreated control (7,593 seeds m^{-2}). Sequential POST triflusulfuron methyl–containing treatments reduced GR sugar beet root and sucrose yields to 18 and 20%, respectively. Consistent with GR canola control, sugar beet root and sucrose yields were highest (95 and 91% of hand-weeded plots, respectively) when the sequential POST triflusulfuron methyl–containing treatments were preceded by ethofumesate (4,200 g ha^{-1}) PRE. Growers should utilize these effective herbicide programs to control volunteer GR canola in GR sugar beet. Because of high canola seed production potential, as evident from this research, control efforts should be aimed at preventing seed bank replenishment of the GR canola volunteers.

Nomenclature: Desmedipham; ethofumesate; glyphosate; phenmedipham; triflusulfuron methyl; canola, *Brassica napus* L.; sugar beet, *Beta vulgaris* L.

Key words: Crop volunteer, glyphosate-resistant canola, glyphosate-resistant sugar beet, herbicide efficacy.

La presencia de colza resistente a glyphosate (GR) voluntaria representa una preocupación para el manejo del cultivo para los productores de remolacha azucarera GR en las Grandes Planicies del Norte. Se realizaron experimentos de campo en el Centro de Investigación Agrícola del Sur cerca de Huntley, Montana, en 2011 y 2012, para evaluar la efectividad de programas de herbicidas para el control de colza GR voluntaria en campos de remolacha azucarera GR. Una sola aplicación POST de triflusulfuron methyl en el estadio de dos hojas de la remolacha fue más efectiva a 35 que a 17.5 g ai ha^{-1}. Sin embargo, las diferencias en entre las dosis no fueron evidentes cuando triflusulfuron methyl fue aplicado con un programa secuencial POST (aplicación en el estadio de dos hojas seguido de [fb] aplicación en el estadio de seis hojas de la remolacha, a 17.5 fb 17.5, ó 35 fb 35 g ha^{-1}). En los tratamientos POST secuenciales con triflusulfuron methyl, las plantas voluntarias de colza GR produjeron poca biomasa (11 a 15% en comparación con las parcelas sin tratamiento), pero sí una cantidad significativa de semilla (160 a 661 semillas m^{-2}). Ethofumesate (4,200 g ai ha^{-1}) PRE seguido de triflusulfuron methyl POST secuencial (17.5 ó 35 g ha^{-1}) brindó un control efectivo (94 a 98% a 30 d después del tratamiento [DAT]), reducción de biomasa (97%), y prevención de producción de semilla de colza GR voluntaria. No hubo ventaja adicional de agregar, ya sea una pre-mezcla (44.7 g ha^{-1}) de desmedipham + phenmedipham + ethofumesate o ethofumesate (140 g ha^{-1}) a los tratamientos secuenciales POST con triflusulfuron methyl. El tratamiento secuencial POST con sólo ethofumesate (140 fb 140 g ha^{-1}). brindó poco control de colza GR voluntaria a 30 DAT, y las plantas que no fueron controladas produjeron 6,361 semillas m^{-2}, lo cual fue comparable al testigo sin tratamiento (7,593 semillas m^{-2}). La

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aplicación secuencial POST de tratamientos que tenían triflusulfuron methyl redujeron los rendimientos de raíz y sucrose de la remolacha GR 18 y 20%, respectivamente. Consistentemente con el control de colza GR, los rendimientos de raíz y sucrose de la remolacha fueron más altos (95 y 91% comparados con las parcelas con deshierba manual, respectivamente) cuando se realizaron aplicaciones PRE de ethofumesate (4,200 g ai ha^{-1}) seguidas de aplicaciones secuenciales POST con tratamientos que contenían triflusulfuron methyl. Los productores deberían utilizar estos efectivos programas de herbicidas para controlar la colza GR voluntaria en campos de remolacha azucarera GR. Debido al alto potencial de producción de semilla de la colza, como se evidenció en esta investigación, se deberían realizar esfuerzos de control orientados a prevenir el incremento del banco de semillas de la colza GR voluntaria.

Sugar beet is an important commercial crop grown in the Northern Great Plains. North Dakota and Minnesota are the leading sugar beet–producing states in this region (Ali 2004). Montana is ranked sixth, with 3.7% of the total U.S. sugar beet production in 2012 (USDA-NASS 2013). Major sugar beet–growing areas in Montana are located east of the continental divide along the Yellowstone River and areas surrounding its tributaries (Afanasiev 1964). Since its introduction in 2007, glyphosate-resistant (GR) sugar beet represents > 95% of total U.S. sugar beet production (Kniss 2010). The rapid adoption of GR sugar beet is due to effective broad-spectrum weed control efficacy, crop safety, and flexibility of glyphosate compared with conventional sugar beet herbicides (Kemp et al. 2009; Kniss et al. 2012; Wilson et al. 2002). Kniss (2010) estimated that less tillage and lower herbicide costs and greater sucrose yields (over 1.4 t ha^{-1}) with high-yielding GR cultivars could increase net economic returns by \$576 ha^{-1} in GR compared with conventional sugar beet.

Canola is another GR crop often grown in rotation with sugar beet, cereals, or soybean [*Glycine max* (L.) Merr.] in this region (North Dakota, Minnesota, Montana, Colorado, and Idaho) (USDA-ERS 2012). Canola seed loss through pod drop and pod shattering at harvest primarily contributes to volunteer problems in succeeding crop rotations (Cavalieri et al. 2014; Gulden et al. 2003). Seed losses at canola harvest could potentially add 3,000 seeds m^{-2} (equivalent to 5.9% of the canola crop yield) to the soil seed bank in a growing season (Gulden et al. 2003), which could be enough to cause high levels of infestation in the subsequent crop. Furthermore, viable seeds can persist in the soil for 4 to 5 yr after the canola crop (Simard et al. 2002), although the majority of seeds germinate in the first year after harvest (Gulden et al. 2004; Harker et al. 2006). In a study conducted in western Canada, volunteer canola seedling recruitment was observed 1 to 3 yr after canola production (Gulden et al. 2004), which might be a concern for growers. Seed burial through tillage and secondary seed dormancy further contributes to the persistence of volunteer canola (Gulden et al. 2004). Glyphosate, glufosinate, and imidazolinone genetically engineered herbicide-resistant (HR) canola cultivars are commercially available. Nevertheless, canola is an allotetraploid with an average outcrossing rate of 21.8%, suggesting a potential for pollen-mediated dispersal of single or multiple HR traits to weedy relatives and conventional canola cultivars (Hall et al. 2000; Rakow and Woods 1987).

Crop volunteers that emerge in subsequent crops are weeds. These volunteers reduce yield of the planted crop by competing for nutrients, moisture, and light; serve as alternative hosts for diseases and insect pests; and interfere with harvest operations (O'Donovan et al. 2008; Ogg and Parker 2000; Williams and Boydston 2006). In western Canada, volunteer canola is rated as one of the most troublesome weeds in agronomic crops (Leeson et al. 2005). GR volunteers in GR crops further complicate the problem because of a limited choice of effective herbicides (Beckie and Owen 2007; Raybould and Gray 1994; York et al. 2005). Interference and yield losses caused by GR volunteers in GR crops such as corn (*Zea mays* L.), soybean, cotton (*Gossypium hirsutum* L.), or sugar beet in rotation have been previously reported (Deen et al. 2006; Kniss et al. 2012; Marquardt and Johnson 2013; York et al. 2005). For instance, early-season competition from volunteer GR corn reduced GR soybean yields by 55 to 68% (Deen et al. 2006). Similarly, Kniss et al. (2012) reported that early-season interference of volunteer GR corn at a density of 1 plant m^{-2} can reduce sucrose yields by 19 to 45% in GR sugar beet.

Volunteer canola (non-HR) interference in rotational crops such as corn, soybean, wheat (*Triticum aestivum* L.), dry pea (*Pisum sativum* L.), flax (*Linum usitatissimum* L.), and sunflower

(*Helianthus annuus* L.) has been documented (Jenks et al. 2006; Rainbolt et al. 2004). O'Donovan et al. (2008) reported that volunteer canola at densities of 50 plants m^{-2} reduced wheat yield by 13 to 49%, depending on the time of emergence of volunteers in the wheat crop. With recent increase in GR canola production in this region (Devine and Buth 2001), there is an increased concern for the occurrence of GR canola volunteers in GR crops grown in rotation, including GR sugar beet.

Herbicides are the most common and effective tools to control canola volunteers in agronomic crops (Beckie et al. 2006; Légère et al. 2006; Rainbolt et al. 2004). Alternative herbicides such as 2,4-D or MCPA (synthetic auxins, Group 4) in wheat, metribuzin (photosystem II inhibitor, Group 5) in soybean, and metsulfuron (ALS inhibitor, Group 2) have been found effective in controlling single-HR, multiple-HR, or non-HR canola volunteers (Beckie et al. 2004, 2006; Légère et al. 2006; Rainbolt et al. 2004). There appears to be no published information on herbicide options to control volunteer GR canola in GR sugar beet. Objectives of this research were to determine effective PRE and POST herbicide programs to control volunteer GR canola in GR sugar beet and to determine their effect on both root and sucrose yield.

Materials and Methods

Field experiments were conducted at the Montana State University Southern Agricultural Research Center near Huntley, MT, in 2011, and repeated in 2012. The soil type was Fort Collins clay loam (fine-loamy, mixed, superactive, mesic Aridic Haplustalfs) with 2.8% organic matter and pH 7.8. The test site was under a sugar beet–barley rotation for the past 5 yr before initiation of the study; glyphosate (840 g ae ha^{-1}) was used for weed control in GR sugar beet, and bromoxynil plus MCPA (1.12 kg ai ha^{-1}) and pinoxaden (60 g ai ha^{-1}) was used for weed control in the barley crop. Seedbed preparation included disking in the fall followed by field cultivation and leveling in the spring before sugar beet planting. Test plots were fertilized with nitrogen–phosphorus–potash as per Montana State University recommendations for sugar beet production (Jacobson et al. 2005). A preseeding application of glyphosate at 840 g ae ha^{-1} was made to control existing weeds in the field. Selected field sites had no history of canola production; therefore, seeds of GR canola hybrid 'DKL 30–42' (Dekalb® Brand, Monsanto Company, 800 North Lindbergh Boulevard, St. Louis, MO 63167) were uniformly broadcast in each plot using a hand spreader at the rate of 1.5 kg ha^{-1} to simulate an infestation of volunteer GR canola. Canola seeds were incorporated into the soil 1.5 cm deep with a light harrow immediately before sugar beet planting. GR sugar beet variety 'BTS 39RR8N RP' (Genuity® Brand, Monsanto) was planted at a rate of 119,500 seeds ha^{-1} in six 61-cm rows on April 20, 2011, and April 26, 2012. GR canola seedlings emerged 3 to 5 d after planting, and GR sugar beet seedlings emerged approximately 7 to 10 d after planting. Sugar beet was irrigated using a overhead linear sprinkler system as per the local standard. All herbicides were applied at their labeled field use rates as either single POST at the two-leaf stage of sugar beet or sequential POST at the two-leaf followed by (fb) six-leaf stage (15 d after the single POST) in the presence or absence of a PRE treatment. All treatments consisted of various rates and application timings of the following three herbicides: triflusulfuron methyl (Upbeet®, Dupont, Wilmington, DE), a prepackaged mixture of desmedipham + phenmedipham+ ethofumesate (Progress®, Bayer CropScience, Research Triangle Park, NC), and ethofumesate (Norton®, Bayer CropScience). Individual treatments are described in Tables 1–3. A nontreated control and a hand-weeded check were included for comparison. Plots were kept free from all other weeds by spraying glyphosate (840 g ae ha^{-1}) three times during the growing season. All herbicide treatments were applied with a CO_2-pressurized backpack sprayer equipped with flat-fan spray nozzles (TeeJet 8001XR, Spraying Systems Co., P.O. Box 7900, Wheaton, IL), calibrated to deliver 94 L ha^{-1} of spray solution at 276 kPa.

A randomized complete block design with four replications was used. Individual plots were 3 m wide by 10 m long. Canola densities were recorded within two 1-m^2 quadrats placed at the center of each plot. Percent control of volunteer GR canola was visually assessed at 7, 15, and 30 d after treatment (DAT) using a scale of 0% (no control) to 100% (complete control). At physiological maturity, aboveground canola biomass was hand-

Table 1. Visual control ratings of volunteer GR canola with various herbicide programs applied to GR sugar beet. Experiments conducted near Huntley, MT; data pooled over 2011 and 2012.[a–e]

Herbicides	Rates	Timings	Canola control 15 DAT	Canola control 30 DAT
	(g ai ha^{-1} or g ae ha^{-1})		%	%
Tri	17.5	2-lf	55 f	57 e
Tri	35	2-lf	65 de	71 d
Tri fb tri	17.5 fb 17.5	2-lf fb 6-lf	57 f	72 cd
Tri fb tri	35 fb 35	2-lf fb 6-lf	66 de	74 cd
Tri fb tri	17.5 fb 35	2-lf fb 6-lf	57 f	73 cd
Tri fb tri	35 fb 17.5	2-lf fb 6-lf	66 de	74 cd
(Tri + DPE) fb (tri + DPE)	(17.5 + 44.7) fb (17.5 + 44.7)	2-lf fb 6-lf	59 ef	74 cd
(Tri + DPE) fb (tri + DPE)	(35 + 44.7) fb (35 + 44.7)	2-lf fb 6-lf	68 cd	76 bc
(Etho + tri) fb (etho + tri)	(140 + 17.5) fb (140 + 17.5)	2-lf fb 6-lf	60 ef	73 cd
(Etho + tri) fb (etho + tri)	(140 + 35) fb (140 + 35)	2-lf fb 6-lf	69 cd	76 bc
Etho fb etho	140 fb 140	2-lf fb 6-lf	18 h	32 f
Etho fb (etho + tri) fb tri	4,200 fb (140 + 17.5) fb 17.5	PRE fb 2-lf fb 6-lf	90 ab	95 a
Etho fb (etho + tri) fb tri	4,200 fb (140 + 35) fb 35	PRE fb 2-lf fb 6-lf	95 a	98 a
Etho fb tri fb tri	4,200 fb 17.5 fb 17.5	PRE fb 2-lf fb 6-lf	90 ab	94 a
Etho fb tri fb tri	4,200 fb 35 fb 35	PRE fb 2-lf fb 6-lf	93 a	95 a

[a] Abbreviations: GR, glyphosate-resistant; tri, triflusulfuron methyl; DPE, desmedipham + phenmedipham + ethofumesate; etho, ethofumesate; lf, true-leaf; fb, followed by.

[b] Application timing corresponded to GR sugar beet growth stages.

[c] All POST treatments were tank-mixed with glyphosate at 840 g ha^{-1}.

[d] All POST treatments included methylated seed oil (MSO) at 1.5% (v/v) and ammonium sulfate (AMS) at 2% (wt/v), except POST ethofumesate-alone treatment.

[e] Means within a column followed by the same letter are not significantly different based on Fisher's protected LSD test at $P < 0.05$.

harvested from two 1-m^2 quadrats placed at the center of each plot, and the dry weight was determined after oven-drying at 60 C for 3 d. Canola seeds were separated from the pods, cleaned, and manually counted. Two center rows of sugar beet were harvested in each plot using a mechanical digger on September 18, 2011, and September 21, 2012. Sugar beet root yield was recorded at this harvest. Root samples were sent to the Western Sugar Cooperative (Billings, MT) for percent sucrose analysis, and sucrose yield for each plot was calculated.

Statistical Analyses. All data were subjected to ANOVA using the MIXED procedure in SAS (version 9.2, SAS Institute Inc., SAS Campus Drive, Cary, NC 27513). Variances were divided into random effects (year, replication [year], and interactions involving either of these two variables) and fixed effects (herbicide treatments). Data on visual estimates of percent control and seed production (no. m^{-2}) were arcsine square root–transformed before analysis to improve the normality of residuals and homogeneity of variance. Canola biomass (% of nontreated) data was log transformed. Nontransformed means are presented in tables based on the analysis from the transformed data. Data from the nontreated plots were not included in the canola percent control analysis. Sugar beet root and sucrose yields were expressed as percentage of hand-weeded treatment. Means were separated using Fisher's protected LSD test at $P < 0.05$.

Results and Discussion

Volunteer GR Canola Control. Volunteer GR canola densities in the GR sugar beet plots averaged 28 to 34 plants m^{-2}. The ratings at 15 DAT represent visual estimates of percent control 15 d after the single POST (twp-leaf stage of sugar beet) or after the first application in the sequential POST (two-leaf followed by six-leaf stage of sugar beet) program; the second application in the sequential POST program was not made until 15 d after the first treatment. Visual symptoms in canola from the PRE application of ethofumesate (4,200 g ha^{-1}) included delayed seedling emergence, leaf cupping

Table 2. Biomass and seed production of volunteer GR canola with various herbicide programs applied to GR sugar beet. Experiments conducted near Huntley, MT; data pooled over 2011 and 2012.[a–e]

Herbicides	Rates	Timings	Biomass	Seed production
	g ai ha^{-1} or g ae ha^{-1}		% nontreated	No. m^{-2}
Tri	17.5	2-lf	58 b	1,913 b
Tri	35	2-lf	16 cd	626 cde
Tri fb tri	17.5 fb 17.5	2-lf fb 6-lf	15 cd	661 cde
Tri fb tri	35 fb 35	2-lf fb 6-lf	14 d	400 de
Tri fb tri	17.5 fb 35	2-lf fb 6-lf	15 cd	609 cde
Tri fb tri	35 fb 17.5	2-lf fb 6-lf	11 de	567 cde
(Tri + DPE) fb (tri + DPE)	(17.5 + 44.7) fb (17.5 + 44.7)	2-lf fb 6-lf	12 de	250 e
(Tri + DPE) fb (tri + DPE)	(35 + 44.7) fb (35 + 44.7)	2-lf fb 6-lf	13 de	160 e
(Etho + tri) fb (etho + tri)	(140 + 17.5) fb (140 + 17.5)	2-lf fb 6-lf	12 de	165 e
(Etho + tri) fb (etho + tri)	(140 + 35) fb (140 + 35)	2-lf fb 6-lf	11 de	177 e
Etho fb etho	140 fb 140	2-lf fb 6-lf	74 a	6,361 a
Etho fb (etho + tri) fb tri	4,200 fb (140 + 17.5) fb 17.5	PRE fb 2-lf fb 6-lf	3 f	0 e
Etho fb (etho + tri) fb tri	4200 fb (140 + 35) fb 35	PRE fb 2-lf fb 6-lf	4 f	0 e
Etho fb tri fb tri	4,200 fb 17.5 fb 17.5	PRE fb 2-lf fb 6-lf	3 f	0 e
Etho fb tri fb tri	4,200 fb 35 fb 35	PRE fb 2-lf fb 6-lf	3 f	0 e
Nontreated	—	—	—	7,593 a

[a] Abbreviations: GR, glyphosate-resistant; tri, triflusulfuron methyl; DPE, desmedipham + phenmedipham + ethofumesate premix; etho, ethofumesate; lf, true leaf; fb, followed by.

[b] All POST treatments were tank-mixed with glyphosate at 840 g ha^{-1}.

[c] Application timing corresponded to sugar beet growth stages.

[d] All POST herbicide treatments included methylated seed oil (MSO) at 1.5% (v/v) and ammonium sulfate (AMS) at 2% (wt/v), except POST ethofumesate-alone treatment.

[e] Means within a column followed by the same letter are not significantly different based on Fisher's protected LSD test at $P < 0.05$.

or puckering, and stunted growth. Visual symptoms in canola from the POST triflusulfuron-containing programs included general chlorosis, stunting, and necrosis. Volunteer GR canola control 15 DAT with triflusulfuron methyl alone at the two-leaf stage of sugar beet (single or sequential POST program) was higher at the 35 g ha^{-1} (66% control) compared with 17 g ha^{-1} rate (56% control) (Table 1). Among all treatments, ethofumesate (4,200 g ha^{-1}) PRE followed by POST triflusulfuron methyl (17.5 or 35 g ha^{-1}) alone or in combination with ethofumesate (140 g ha^{-1}) at the two-leaf timing was the most effective, with control averaging 90 to 95%. Control 15 DAT was least (18%) with ethofumesate (140 g ha^{-1}) alone applied POST.

The 30 DAT ratings represent visual estimates of percent control 30 d after the single POST (two-leaf stage of sugar beet) or 15 d after the second application in the sequential POST (two-leaf followed by six-leaf stage of sugar beet) program. Ethofumesate PRE followed by sequential POST triflusulfuron methyl applied at 17.5 fb 17.5 g ha^{-1} or 35 fb 35 g ha^{-1} controlled volunteer GR canola by 94 to 98% in GR sugar beet 30 DAT, irrespective of adding ethofumesate (140 g ha^{-1}) POST (Table 1). Control 30 DAT with single POST triflusulfuron methyl was 71% at the 35 g ha^{-1} rate compared with 57% at the 17.5 g ha^{-1} rate. Furthermore, control with the single POST triflusulfuron methyl at the 35 g ha^{-1} rate did not differ from sequential POST triflusulfuron methyl treatments (17.5 or 35 g ha^{-1} fb 17.5 or 35 g ha^{-1}). Addition of desmedipham + phenmedipham + ethofumesate premix (44.7 g ha^{-1}) or ethofumesate (140 g ha^{-1}) did not further improve control compared with the sequential POST triflusulfuron methyl–only treatments. Consistent with the 15 DAT rating, ethofumesate only applied sequential POST (140 fb 140 g ha^{-1}) was the least effective treatment.

Volunteer GR Canola Biomass. Consistent with the control ratings, ethofumesate (4,200 g ha^{-1}) PRE followed by sequential POST triflusulfuron methyl alone (either 17.5 fb 17.5 g ha^{-1} or 35 fb 35 g ha^{-1}) treatment reduced (97% average of nontreated) volunteer GR canola biomass the most; no additional benefit was observed from tank-mixing

Table 3. GR sugar beet root and sucrose yield with various herbicide programs applied for volunteer GR canola control. Experiments conducted near Huntley, MT; data pooled over 2011 and 2012.[a–e]

Herbicides	Rates	Timings	Root yield	Sucrose yield
	g ai ha^{-1} or g ae ha^{-1}		—% of hand-weeded—	
Tri	17.5	2-lf	67 f	67 g
Tri	35	2-lf	80 e	78 def
Tri fb tri	17.5 fb 17.5	2-lf fb 6-lf	79 e	79 def
Tri fb tri	35 fb 35	2-lf fb 6-lf	80 e	79 def
Tri fb tri	17.5 fb 35	2-lf fb 6-lf	81 de	80 def
Tri fb tri	35 fb 17.5	2-lf fb 6-lf	82 de	80 def
(Tri + DPE) fb (tri + DPE)	(17.5 + 44.7) fb (17.5 + 44.7)	2-lf fb 6-lf	79 e	77 ef
(Tri + DPE) fb (tri + DPE)	(35 + 44.7) fb (35 + 44.7)	2-lf fb 6-lf	85 cde	82 cde
(Etho + tri) fb (etho + tri)	(140 + 17.5) fb (140 + 17.5)	2-lf fb 6-lf	83 cde	80 def
(Etho + tri) fb (etho + tri)	(140 + 35) fb (140 + 35)	2-lf fb 6-lf	84 cde	82 cde
Etho fb etho	140 fb 140	2-lf fb 6-lf	55 g	50 h
Etho fb (etho + tri) fb tri	4,200 fb (140 + 17.5) fb 17.5	PRE fb 2-lf fb 6-lf	92 ab	88 abc
Etho fb (etho + tri) fb tri	4,200 fb (140 + 35) fb 35	PRE fb 2-lf fb 6-lf	96 a	92 ab
Etho fb tri fb tri	4,200 fb 17.5 fb 17.5	PRE fb 2-lf fb 6-lf	95 a	92 ab
Etho fb tri fb tri	4,200 fb 35 fb 35	PRE fb 2-lf fb 6-lf	96 a	94 a
Nontreated	—	—	50 g	47 h

[a] Abbreviations: GR, glyphosate-resistant; tri, triflusulfuron methyl, DPE, desmedipham + phenmedipham + ethofumesate premix; etho, ethofumesate; lf, true leaf; fb, followed by.

[b] All POST treatments were tank mixed with glyphosate at 840 g ha^{-1}.

[c] Application timing corresponded to sugar beet growth stages.

[d] All POST treatments included methylated seed oil (MSO) at 1.5% (v/v) and ammonium sulfate (AMS) at 2% (wt/v), except POST ethofumesate-alone treatment.

[e] Means within a column followed by the same letter are not significantly different based on Fisher's protected LSD test at $P < 0.05$.

ethofumesate (140 g ha^{-1}) POST (Table 2). Single POST triflusulfuron methyl applied at 35 g ha^{-1} reduced GR canola biomass by 84% compared with 42% of the nontreated control when applied at 17.5 g ha^{-1}. Furthermore, canola biomass reduction with single POST triflusulfuron methyl at the 35 g ha^{-1} rate did not differ from any of the sequential POST triflusulfuron methyl–containing treatments and averaged 87% of the nontreated control (Table 2). Similar to the control ratings, no additional advantage was observed on GR canola biomass reduction by tank mixing either desmedipham + phenmedipham + ethofumesate (44.7 kg ha^{-1}) premix or ethofumesate (140 g ha^{-1}) with the sequential POST triflusulfuron methyl–only treatment. Noncontrolled volunteer GR canola in the sequential POST ethofumesate-only treatment produced a significant amount of biomass (i.e., 74% of the nontreated).

Volunteer GR Canola Seed Production. Consistent with effective control and biomass reduction, ethofumesate PRE (4,200 g ha^{-1}) followed by POST triflusulfuron methyl alone applied sequentially at either 17.5 fb 17.5 g ha^{-1} or 35 fb 35 g ha^{-1} prevented any volunteer GR canola seed production (Table 2). There was no additional benefit of adding either ethofumesate or desmedipham + phenmedipham + ethofumesate premix to the sequential POST triflusulfuron methyl–only treatments. Seed production with a single POST triflusulfuron methyl was significantly less at the 35 g ha^{-1} (626 seeds m^{-2}) rate compared with the 17.5 g ha^{-1} (1,913 seeds m^{-2}) rate. Also, seed production with a single POST triflusulfuron methyl at the 35 g ha^{-1} rate did not differ from any of the sequential POST programs (in the absence of ethofumesate PRE), except for the sequential POST ethofumesate-only (140 fb 140 g ha^{-1}) treatment. Volunteer GR canola plants in the sequential POST ethofumesate-only treatment produced 6,361 seeds m^{-2}, which was no different from the nontreated control (7,593 seeds m^{-2}).

GR Sugar Beet Root and Sucrose Yields. Season-long interference of volunteer GR canola in nontreated control reduced GR sugar beet root and sucrose yields by 50 and 53% of the hand-weeded control, respectively (Table 3). Consistently, the ethofumesate (4,200 g ha^{-1}) PRE followed by sequential POST triflusulfuron methyl (17.5 or 35 g ha^{-1}) treatments had the highest root and sucrose yields, which averaged 95 and 92% of the hand-weeded control, respectively. After ethofumesate PRE, there was no benefit of adding ethofumesate (140 g ha^{-1}) to the POST sequential triflusulfuron methyl–only treatments for sugar beet yields. Root and sucrose yields (80 and 78% of hand-weeded, respectively) were significantly higher with the single POST triflusulfuron methyl applied at 35 compared with 17.5 g ha^{-1}. Furthermore, sugar beet yields with the single POST triflusulfuron methyl at 35 g ha^{-1} did not differ from any of the sequential POST triflusulfuron-containing programs in the absence of ethofumesate PRE. Among all herbicide treatments, the lowest root (55% of hand-weeded) and sucrose yields (50% of hand-weeded) were obtained with the sequential POST ethofumesate-only treatment.

In conclusion, volunteer GR canola at densities of approximately 30 plants m^{-2} caused severe interference in GR sugar beet and reduced sucrose yields by 53%. If not managed, uncontrolled canola plants could add a significant number of seeds (7,593 seeds m^{-2}) to the soil seed bank for presence of GR volunteers in subsequent crops. Furthermore, the potential risk of pollen-mediated gene flow of the transgenic HR trait from the GR canola volunteers to weedy relatives and non-HR canola (Beckie et al. 2004; Hall et al. 2000) warrants attention for effective control of the volunteers. Based on this research, ethofumesate (4,200 g ha^{-1}) PRE followed by sequential POST triflusulfuron methyl ($\geq$ 17.5 g ha^{-1}) would be an effective herbicide program to prevent seed bank replenishment of volunteer GR canola and prevent yield reductions in GR sugar beet. Canola can emerge earlier than sugar beet; nevertheless, plants exhibit winter hardiness, resulting in lower efficacy of POST herbicides applied in the spring (Légère et al. 2006). Therefore, targeting the seed bank with PRE herbicides early in the spring (e.g., ethofumesate PRE at the full, recommended rate in sugar beet) will aid in reducing volunteer canola interference in the crop. This field-based research is one of the first attempts to address this issue and will add to the knowledge on available herbicide tools to manage volunteer HR canola.

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