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Interaction between Preemergence Ethofumesate and Postemergence Glyphosate

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Greenhouse and field experiments were conducted to determine whether PRE-applied ethofumesate increased POST spray retention and weed control with glyphosate. In greenhouse studies, ethofumesate was applied PRE at rates from 0 to 224 g ai ha^{-1} followed by POST treatment with either water or glyphosate (840 g ae ha^{-1}) to which a red dye had been added. Plants were immediately washed and spray retention determined spectrophotometrically. Common lambsquarters retained more glyphosate solution compared to water, regardless of PRE ethofumesate rate. Increasing the rate of PRE ethofumesate increased the POST spray retention of both water and glyphosate. PRE application of ethofumesate increased POST spray retention of water by 114% and glyphosate solution by 18% compared to no ethofumesate treatment as determined by nonlinear regression. Ethofumesate rates of 90 g ha^{-1} increased POST spray retention to at least 95% of the total observed response. In field studies, common lambsquarters, redroot pigweed, and hairy nightshade densities were all reduced by ethofumesate, although the duration of ethofumesate effect varied by species and ethofumesate application timing. PRE ethofumesate had no significant effect on hairy nightshade density until after POST glyphosate was applied, whereas common lambsquarters densities were most affected by PRE ethofumesate early in the season. Late-season redroot pigweed density was reduced by ethofumesate regardless of application timing.

Nomenclature: Ethofumesate; glyphosate; common lambsquarters, *Chenopodium album* L.; hairy nightshade, *Solanum sarrachoides* auct. non Sendtner; redroot pigweed, *Amaranthus retroflexus* L.
Key words: Herbicide interaction, retention, sugarbeet, very long chain fatty acid synthesis.

Se realizaron experimentos de campo y de invernadero para determinar si ethofumesate aplicado PRE incrementó la retención de aplicaciones de glyphosate POST y el control de malezas. En los estudios de invernadero, ethofumesate fue aplicado PRE a dosis de 0 a 224 g ha^{-1} seguidos de tratamientos POST con agua o glyphosate (840 g ae ha^{-1}) a los cuales se les había agregado un colorante rojo. Las plantas fueron lavadas inmediatamente y la retención fue determinada espectrofotométricamente. *Chenopodium album* retuvo más glyphosate al compararse con agua, sin importar la dosis PRE de ethofumesate. Al incrementarse la dosis PRE de ethofumesate se aumentó la retención de las aplicaciones POST de agua y glyphosate. La aplicación PRE de ethofumesate incrementó la retención de agua POST en 114% y la de glyphosate en 18% en comparación al tratamiento sin ethofumesate, como se determinó usando regresiones no lineales. Dosis menores a 90 g ha^{-1} de ethofumesate incrementaron la retención de aplicaciones POST al 95% del total de respuestas observadas. En los estudios de campo, las densidades de *C. album*, *Amaranthus retroflexus* y *Solanum sarrachoides* fueron todas reducidas por ethofumesate, aunque la duración del efecto de ethofumesate varió según la especie y el momento de aplicación de ethofumesate. Ethofumesate PRE no tuvo ningún efecto en la densidad de *S. sarrachoides* hasta después de que se aplicó glyphosate POST, mientras que las densidades de *C. album* se vieron más afectadas por ethofumesate PRE, temprano en la temporada. La densidad de *A. retroflexus*, tarde en la temporada, fue reducida por ethofumesate sin importar el momento de aplicación.

Ethofumesate is a herbicide registered for use either PRE or POST in sugarbeet (*Beta vulgaris* L.). Ethofumesate inhibits the biosynthesis of very long chain fatty acids (VLCFAs), although the specific mechanism of herbicidal action is not clearly understood (Abulnaja et al. 1992; Devine et al. 1993; Senseman 2007). Ethofumesate is readily absorbed by emerging shoots and roots and translocated rapidly to the foliage, although virtually no basipetal translocation is observed (Eshel et al. 1978). When applied PRE at 800 g ai ha^{-1} under greenhouse conditions, ethofumesate decreased epicuticular wax in cabbage (*Brassica oleracea* L.) leaves by nearly 60% (Leavitt et al. 1979) and in onion (*Allium cepa* L.) leaves by 66% (Rubin et al. 1986). Recommended field use rates of ethofumesate for PRE application in sugarbeet range from 1.25 to 4.2 kg ai ha^{-1}, depending on soil characteristics and weed pressure. Rubin et al. (1986) found that the rate response reaches a plateau with respect to wax reduction at far less than the field use rate, as 400 g ha^{-1} resulted in a 66% reduction in epicuticular waxes. This result indicates that sublethal rates of ethofumesate may be sufficient to disrupt leaf waxes that represent a significant impediment to POST herbicide retention and absorption.

In addition to decreasing the amount of wax, ethofumesate alters the structure of waxes (Rubin et al. 1986). When the wax structure is altered in this manner, increased transpiration of water from the leaf surface can be observed, which in turn results in increased uptake of other soil-applied herbicides that are transported through the xylem (Devine et al. 1993). Ethofumesate has been documented to increase uptake of foliage-applied herbicides when applied prior to (Devine et al. 1993; Duncan et al. 1982; Rubin et al. 1986) or at the same time as other herbicides (Eshel et al. 1976). Whether the

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observed increase in absorption results in increased phytotoxicity depends on the herbicide mode of action (Rubin et al. 1986).

Herbicides that inhibit VLCFA biosynthesis cause a reduction in chain lengths of free fatty acids that is proportional to the dose applied (Bolton and Harwood 1976); therefore, even if the herbicide is applied at sublethal rates, epicuticular wax formation and composition are affected. In addition to increasing penetration of foliage-applied herbicides by reducing epicuticular waxes (Duncan et al. 1982), VLCFA-inhibiting herbicides have also shown potential to increase spray retention and decrease droplet contact angle of subsequently applied herbicides (Gentner 1966). However, there have been no studies investigating the effect of PRE ethofumesate on POST spray retention.

Common lambsquarters has long been recognized as one of the most economically-damaging weeds to sugarbeet production (Holm et al. 1977). This weed has been previously recognized as being difficult to control with glyphosate (Kniss et al. 2007; Westhoven et al. 2008). The leaf surface of common lambsquarters is composed of 66% polar components, compared to 55 and 11% for redroot pigweed, and black nightshade (*Solanum nigrum* L.), respectively (Harr et al. 1991). The epicuticular wax of common lambsquarters is crystalline in structure, and consequently will retain less herbicide spray solution compared to smooth cuticular surfaces (De Ruiter et al. 1990; Harr et al. 1991). A 0.1% surfactant solution in water results in a spray droplet contact angle of 76° on common lambsquarters leaves, compared to 54° and 34° for redroot pigweed, and black nightshade, respectively (Harr et al. 1991). This low wettability of the common lambsquarters leaf surface may lead to poor herbicide efficacy because of reduced spray retention and herbicide absorption. Ramsdale and Messersmith (2001) found that retention of a water–dye spray mixture was minimal on common lambsquarters, retaining only 25% as much of the mixture as similarly treated redroot pigweed. It is likely that reduced spray retention contributes to variable control of common lambsquarters with glyphosate.

Use of glyphosate for weed control in glyphosate-resistant sugarbeet increases sucrose yield and net economic returns compared to conventional sugarbeet herbicides used in conventional sugarbeet (Kemp et al. 2009; Kniss et al. 2004; Kniss 2010; Wilson et al. 2002). Economic benefits of the glyphosate-resistant system are derived from increased weed control and decreased crop injury, which both contribute to increased sucrose yield. Odero et al. (2008) demonstrated that PRE ethofumesate resulted in over \$200 ha^{-1} greater net economic return when used in conventional sugarbeet compared to no PRE treatment. However, growers may be hesitant to use ethofumesate in glyphosate-resistant sugarbeet because of its potential for crop injury (Wilson 1999; Wilson et al. 1990, 2002). Even if commercial levels of weed control are not achieved, reduced rates of ethofumesate may provide weed control benefit if it increases retention or absorption of subsequently applied herbicides. While ethofumesate has been previously shown to increase uptake and efficacy of subsequently applied herbicides (Duncan et al. 1982), there has been no research published investigating the effect of ethofumesate on retention of subsequently applied herbicides, or on efficacy of subsequently applied glyphosate. The objectives of this study were to determine if sublethal rates of PRE-applied ethofumesate increase POST spray retention on common lambsquarters; and evaluate PRE ethofumesate in field studies in combination with POST glyphosate.

Materials and Methods

Greenhouse Study. A greenhouse study was conducted twice at the University of Wyoming Agricultural Experiment Station in Laramie in May, 2010. Common lambsquarters seeds used in the experiments were collected near Ogallala, NE in 2004 from a population with no previous exposure to ethofumesate or glyphosate for at least the previous 12 years. After collection, seed was stored at 4 C until used in this experiment. The seeds were planted in 10 by 10 cm pots containing a 1 : 2 ratio of sand to commercial potting mix (Sunshine SB 300, Sun Gro Horticulture, Vancouver, BC, Canada). Pots were placed in a greenhouse maintained at 22 C (±3) and a 16 h photoperiod using supplemental metal halide lights. The experimental design was a completely randomized design with six replicates. A two-factorial treatment arrangement was utilized where the first factor was PRE ethofumesate (Nortron® SC, Bayer CropScience, Research Triangle Park, NC) rate (0, 7, 14, 28, 56, and 224 g ai ha^{-1}) and the second factor was POST spray material [either water alone or glyphosate (Honcho® Plus, Monsanto Company, St. Louis, MO) solution at 840 g ae ha^{-1}]. The glyphosate formulation was chosen because the label allowed (but did not require) addition of a nonionic surfactant (NIS). In this way, the formulation was representative of many glyphosate formulations that are widely used in the region. All treatments were applied using a moving-nozzle spray chamber equipped with a single, even flat fan nozzle tip (TeeJet® 8002E, Spraying Systems Co., Wheaton, IL) calibrated to deliver 187 L ha^{-1} of total volume at 276 kPa.

PRE ethofumesate was applied immediately after planting, and the pots were placed in the greenhouse. Common lambsquarters were thinned to one plant per pot after emergence. Plants were watered daily to field capacity and fertilized weekly. POST treatments were applied to common lambsquarters plants at the four- to six-leaf stage. All POST treatments included red dye (FD&C Red # 40, Spectrum Chemical Mfg. Corp., Gardena, CA) at a concentration of 5 g L^{-1}. Immediately after application, each plant was clipped at the soil surface and placed with forceps in a beaker containing 10 ml of water, and vigorously shaken for approximately 20 s to wash off the dye. Plants were removed from the beaker and the total leaf area was measured using a Delta-T leaf area meter. The absorbance of the wash solution was measured at 505 nm with a Genesys 20 spectrophotometer (Geneq Inc., Montreal, QC, Canada). The amount of spray solution retained by the plant was then calculated from the absorbance at 505 nm from a standard curve that had been generated previously ($R^2 = 0.99$). Spray retention was then divided by the leaf area of the plant and is presented as μL of spray solution per cm^2 of common lambsquarters leaf area ($\mu\text{l cm}^{-2}$).

A mixed effects ANOVA was conducted on POST spray retention per cm^2 of leaf area with PRE ethofumesate rate, POST spray material, and the interaction between these two factors as fixed effects. Experimental run was considered a random effect. Nonlinear regression was then performed to quantify the effect of PRE ethofumesate rate on POST spray retention. The log–logistic model (Equation 1) as described by Seefeldt et al. (1995) was fitted using the drc package in R (R Development Core Team 2009; Ritz and Streibig 2005):

$$f(x) = c + \left\{(d - c)/1 + \exp\left[b\left(\log(x) - \log(e)\right)\right]\right\} \quad [1]$$

where c and d are the lower and upper limits, respectively; b is the slope around the inflection point; e is the dose of ethofumesate causing 50% response; and x is the rate of ethofumesate.

Field Study. A field study was conducted in 2009 and repeated in 2011. Ethofumesate was applied at 0, 280, 560, and 1,120 g ha^{-1} in three different use patterns in combination with glyphosate (Roundup WeatherMax®, Monsanto Company, St. Louis, MO). Ethofumesate use patterns were chosen based on application timings that would be considered by sugarbeet growers. It is unlikely that sugarbeet growers will apply ethofumesate as a stand-alone treatment, but they may consider applying ethofumesate at planting, or as a tank mixture with either the first or second application of glyphosate in order to reduce application costs.

The first use pattern used in the study was ethofumesate PRE followed by one POST application of glyphosate at the sugarbeet 2 true-leaf stage. This treatment was not expected to provide season-long weed control, and a second POST treatment of glyphosate would be used in practice; for the purpose of this study, a second POST treatment was not applied to better assess residual weed control and interactions between PRE ethofumesate and POST glyphosate.

The second use pattern was a tank mixture of ethofumesate plus glyphosate applied at the 2 true-leaf stage followed by a second POST application of glyphosate at the 8 to 10 true-leaf stage. The third use pattern was an application of glyphosate at the 2 true-leaf stage, followed by a tank mixture of ethofumesate plus glyphosate at the 6 true-leaf stage. Glyphosate was applied at 560 g ha^{-1} in all use patterns. PRE applications were made on April 22, 2009 and April 26, 2011. Two true-leaf treatments were applied on May 18, 2009 and May 25, 2011. Six true-leaf treatments were applied on June 8, 2009 and June 8, 2011. Eight to 10 true-leaf treatments were applied on June 13, 2009 and June 15, 2011.

Weeds in each plot were counted in a 0.45 m^2 area at the time of the first and second POST herbicide treatments, in late June, and again in mid-July. Sugarbeet yield was determined by harvesting one row in each plot in late October. The experiment was a randomized complete block design with three replicates in 2009 and four replicates in 2011. Plots were 3 by 9 m in both years. Weed density and yield data were analyzed with a linear mixed-effects model, with year considered a random effect, and ethofumesate rate and application timing as fixed effects. Linear regression equations are provided for weed density in response to ethofumesate rate for each weed species, application timing, and evaluation date.

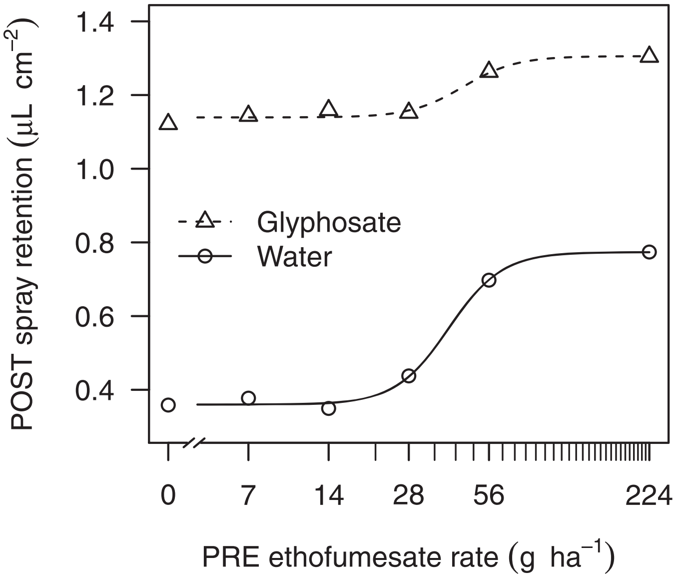

Figure 1. POST spray retention of water and glyphosate on common lambsquarters as influenced by PRE ethofumesate.

Results and Discussion

Greenhouse Study. Spray retention was influenced by the interaction of PRE ethofumesate rate and POST spray material ($P = 0.0246$); therefore, spray retention was modeled as a function of PRE ethofumesate rate for each POST spray material using the log–logistic model (Equation 1). Common lambsquarters retained more glyphosate solution compared to water (Figure 1). The glyphosate formulation used in this study allows addition of a nonionic surfactant but does not require one, and thus it is likely that a surfactant system is included in the formulated product. This is consistent with previous research by Ramsdale and Messersmith (2001) demonstrating that common lambsquarters has a very difficult to wet leaf surface, and that adjuvants significantly increase retention on this species compared to water alone.

PRE application of ethofumesate increased retention of both water and glyphosate applied POST (Figure 1). The c and d parameters in the log–logistic model are the lower and upper asymptotes, respectively, which represent the theoretical minimum and maximum retention on common lambsquarters in response to PRE ethofumesate. The difference between the maximum and minimum retention predicted by the model provides an estimate of the amount of POST spray retention that can be attributed to PRE application of ethofumesate. For water applied POST, the difference between the d and c parameters is 0.41 $\mu\text{l cm}^{-2}$, which equates to a 114% increase in spray retention compared to no ethofumesate treatment (Table 1). These results clearly demonstrate that the VLCFA disruption caused by ethofumesate applied PRE allows for increased POST spray

Table 1. Log-logistic model parameter estimates for POST water and glyphosate spray retention on common lambsquarters in response to PRE ethofumesate.

POST material	Parameter estimate[a] (std. err.) *b*	*c*	*d*	*e*	Maximum increase in POST retention caused by PRE ethofumesate
					%
Water	−4.3(2.67)	0.36(0.045)	0.77(0.074)	40(10.0)	114
Glyphosate	−4.4(7.79)	1.1(0.042)	1.3(0.069)	45(24.4)	18

[a] Parameter estimates are described in Equation 1.

retention. The dose of PRE ethofumesate required to cause 95% of the maximum POST retention (ED_{95}) was predicted to be 78 and 88 g ha^{-1} for water and glyphosate solution, respectively. This is consistent with preliminary data that showed no significant increase in retention at PRE ethofumesate rates greater than 112 g ha^{-1} (data not shown).

Use of ethofumesate PRE is not as effective at increasing POST spray retention as the adjuvant system contained in the glyphosate formulation; the minimum retention (*c* parameter) of the POST glyphosate treatment was greater than the maximum retention (*d* parameter) of the POST water treatment (Table 1). The PRE application of ethofumesate resulted in an additional increase in POST spray retention of glyphosate (Figure 1). The difference between the *d* and *c* parameters for the glyphosate POST treatment was 0.2 μl cm^{-2}, which represents an 18% increase in POST spray retention compared to no ethofumesate PRE (Table 1). Taken together these results indicate that ethofumesate PRE, even when applied at rates that are not lethal to common lambsquarters, increase retention of subsequently applied herbicide treatments.

Field Study. There was a significant ethofumesate rate response in common lambsquarters, redroot pigweed, and hairy nightshade when ethofumesate was applied PRE (Table 2); however, there was a difference between species as to when the response was observed. When weeds were counted at the time of the first POST glyphosate treatment (2 true-leaf stage), common lambsquarters and redroot pigweed densities were significantly reduced by increasing rates of ethofumesate, whereas hairy nightshade densities were not affected. Common lambsquarters density was reduced 40, 63, and 85% at ethofumesate rates of 280, 560, and 1,120 g ha^{-1}, respectively. Redroot pigweed density was reduced 57, 89, and 99% at the same ethofumesate rates. Reduced rates of ethofumesate (280 or 560 g ha^{-1}) did not provide what would be considered commercially acceptable control of these species, but the densities were significantly reduced compared to no PRE treatment. Although not commercially acceptable on its own, this reduction in weed density may still be beneficial as it reduces the number of weeds competing with the sugarbeet crop early in the season. Additionally, reduced weed density resulted in fewer individuals exposed to POST applications of glyphosate, thereby reducing the selection pressure for glyphosate-resistant biotypes.

The effect of PRE ethofumesate rate on common lambsquarters was no longer significant by the June and July evaluation dates (Table 2). The effect of PRE ethofumesate on

Table 2. Weed density as influenced by ethofumesate PRE and glyphosate POST in glyphosate-resistant sugarbeet near Lingle, WY, 2009 and 2011.

Weed species	Ethofumesate rate	Weed density At POST[a]	2 wk after POST	Late June	Mid-July
	g ai ha^{-1}	plants m^{-2}			
Common lambsquarters:	0	93	103	23	30
	280	56	67	24	26
	560	34	78	14	27
	1,120	14	29	23	17
Equation:		$y = 90-0.067x$	$y = 104-0.059x$	$y = 23-0.001x$	$y = 31-0.011x$
P-value:		< 0.01	0.03	0.84	0.18
R^2:		0.71	0.44	0.29	0.14
Redroot pigweed:	0	37	36	41	25
	280	16	31	30	17
	560	4	9	9	4
	1,120	0.3	3	5	2
Equation:		$y = 31-0.031x$	$y = 38-0.032x$	$y = 40-0.033x$	$y = 24-0.021x$
P-value:		0.02	0.06	0.02	< 0.01
R^2:		0.27	0.26	0.37	0.43
Hairy nightshade:	0	274	213	176	94
	280	257	122	124	83
	560	288	154	182	97
	1,120	196	104	85	44
Equation:		$y = 308-0.065x$	$y = 195-0.078x$	$y = 181-0.067x$	$y = 102-0.042x$
P-value:		0.12	0.04	0.05	<0.01
R^2:		0.77	0.48	0.35	0.33

[a] Glyphosate was applied POST at 560 g ae ha^{-1} when sugarbeet was in the 2 true-leaf stage; weed density was counted 0 to 1 d before POST treatment.

Table 3. Weed density as influenced by ethofumesate and glyphosate mixtures applied in the first POST treatment in glyphosate-resistant sugarbeet near Lingle, WY, 2009 and 2011.

Weed species	Ethofumesate rate[a]	Weed density		
		At 2nd POST[b]	Late June	Mid-July
	g ai ha^{-1}	plants m^{-2}		
Common lambsquarters:	0	89	9	6
	280	65	6	10
	560	59	3	3
	1,120	31	0	0.5
Equation:		$y = 92-0.049x$	$y = 8-0.008x$	$y = 8-0.006x$
P-value:		< 0.01	< 0.01	0.02
R^2:		0.67	0.43	0.17
Redroot pigweed:	0	43	2	3
	280	17	2	4
	560	5	2	2
	1,120	2	0	0
Equation:		$y = 35-0.034x$	$y = 2-0.001x$	$y = 4-0.003x$
P-value:		0.02	0.27	0.04
R^2:		0.28	0.14	0.15
Hairy nightshade:	0	194	52	15
	280	165	33	17
	560	164	24	5
	1,120	91	6	1
Equation:		$y = 208-0.089x$	$y = 45-0.039x$	$y = 15-0.014x$
P-value:		< 0.01	< 0.01	0.02
R^2:		0.68	0.51	0.32

[a] Ethofumesate was applied as a tank mixture with glyphosate POST at 560 g ae ha^{-1} when sugarbeet was in the 2 true-leaf stage.

[b] A second application of glyphosate was applied when sugarbeet was in the 8 true-leaf stage; weed density was counted at the time of this second POST treatment.

redroot pigweed densities were observed at all evaluation dates, with linear regression slopes indicating redroot pigweed density was reduced by 2 to 3 plants m^{-2} for each 100 g ha^{-1} of ethofumesate. Although hairy nightshade density was not significantly reduced by PRE ethofumesate at the time of the POST glyphosate application, densities were reduced by PRE ethofumesate at all subsequent evaluation dates (Table 2). Although these data do not provide direct evidence, it is possible that this reduction in density is due to increased control by glyphosate due to sublethal exposure to ethofumesate, either due to increased retention as shown in the greenhouse study, or increased absorption as demonstrated by previous researchers (Devine et al. 1993; Duncan et al. 1982; Rubin et al. 1986). However, it is also possible that newly emerged weeds counted at the first evaluation date were eventually killed by the ethofumesate, without a direct interaction with POST glyphosate application. Continued reduction in hairy nightshade density as the growing season progressed is likely due to inter- and intraspecific competition.

When ethofumesate was tank-mixed with glyphosate in the first POST application (2 true-leaf sugarbeet stage), a significant rate response was observed for all three weed species at nearly all evaluation dates (Table 3). The exception was redroot pigweed density evaluated in late June, largely because density was ≤ 2 plants m^{-2}. The response to ethofumesate was significant again at the July evaluation timing as more redroot pigweed emerged. Ethofumesate tank-mixed with the first POST glyphosate application reduced common lambsquarters, redroot pigweed, and hairy nightshade density by up to 65, 95, and 53%, respectively, when evaluated at the time of the second POST application. The effect of ethofumesate continued through the July evaluation date, with densities of all three species being reduced by greater than 90% at the 1,120 g ha^{-1} compared with no ethofumesate.

When ethofumesate was tank-mixed with glyphosate in the second POST application (at the 6 true-leaf sugarbeet stage), there was no effect of ethofumesate on common lambsquarters density at either the June or July evaluation dates (Table 4). This is probably because common lambsquarters tends to emerge early in the season compared with redroot pigweed and hairy nightshade, and therefore, late-season application of ethofumesate would provide little benefit for common lambsquarters control. Conversely, hairy nightshade density was reduced by up to 54 and 100% at the June and July evaluation dates, respectively, by application of ethofumesate. Redroot pigweed density was not affected by ethofumesate applied in the final POST application at the June evaluation, but a trend was evident in July. Slope of the linear regression indicated a reduction in redroot pigweed density of 0.7 plants m^{-2} for each 100 g ai ha^{-1} of ethofumesate at this application timing.

Differences in common lambsquarters and redroot pigweed densities between late POST and early POST applications of ethofumesate were probably related to the second POST application timing. When ethofumesate was applied late POST, the final POST treatment was applied at the 6 true-leaf sugarbeet stage. When ethofumesate was applied early POST, the second POST glyphosate application was made at the 8 to 10 true-leaf stage of sugarbeet. The reason for this difference is that application of the residual herbicide early in the season allowed for the second POST herbicide treatment to be delayed further into the season. The residual control from the first POST application reduced the weed density so

Table 4. Weed density as influenced by ethofumesate and glyphosate mixtures applied at in the final POST application in glyphosate-resistant sugarbeet near Lingle, WY, 2009 and 2011.

		Weed density	
Weed species	Ethofumesate rate[a]	Late June	Mid-July
	g ai ha^{-1}	plants m^{-2}	
Common lambsquarters:	0	7	7
	280	4	7
	560	6	10
	1,120	7	3
Equation:		$y = 5-0.001x$	$y = 8-0.003x$
P-value:		0.60	0.20
R^2:		0.08	0.06
Redroot pigweed:	0	4	10
	280	3	6
	560	4	3
	1,120	2	2
Equation:		$y = 4-0.001x$	$y = 8-0.007x$
P-value:		0.38	0.05
R^2:		0.42	0.19
Hairy nightshade:	0	28	11
	280	21	15
	560	15	6
	1,120	13	0
Equation:		$y = 24-0.013x$	$y = 13-0.012x$
P-value:		0.03	0.01
R^2:		0.35	0.37

[a] Ethofumesate was applied as a tank mixture with glyphosate POST at 560 g ae ha^{-1} when sugarbeet was in the 6 true-leaf stage.

that there were very few weeds requiring treatment at the 6 true-leaf stage. If the residual herbicide was not applied early in the season, the second weed flush resulted in far greater densities of surviving weeds and, therefore, required treatment at the 6 true-leaf stage to avoid sugarbeet yield loss.

For all three weed species, and in all three ethofumesate use patterns (PRE, early POST, and late POST), greater weed control was obtained when using ethofumesate at 1,120 g ha^{-1} compared to reduced rates or no ethofumesate; however, reduced ethofumesate rates also significantly reduced the density of weeds compared to no ethofumesate. Sugarbeet yield was not affected by ethofumesate rate within any application timing (data not shown). Although no relationship between yield and sugarbeet injury was observed in this study, previous reports have indicated that ethofumesate can injure sugarbeet when adverse environmental conditions are present (Kniss et al. 2004; Wilson et al. 1990, 2002). Reduced ethofumesate rates will reduce the potential for crop injury as well as reduce the cost of the treatment, and could potentially increase the likelihood that sugarbeet growers will use an alternative herbicide mode of action in glyphosate-resistant sugarbeet. Early applications of ethofumesate (either PRE or early POST), even at reduced rates, will decrease the density of weeds in the field. This will almost certainly allow for the second POST glyphosate application to be made later in the season, which will lead to better overall late-season weed control. Early applications of ethofumesate will also decrease the number of individual weeds exposed to glyphosate in later applications. This will decrease the selection pressure for glyphosate-resistant weeds to develop in sugarbeet rotations. Additionally, early applications of ethofumesate, even at sublethal rates, can increase POST spray retention which in turn could make them more susceptible to POST glyphosate applications. Although the field study did not provide direct evidence of this, the greenhouse study demonstrated that this is at least a possibility that could explain increased weed control with combinations of ethofumesate and glyphosate.

Based on these results, ethofumesate should be applied either PRE or early POST in sugarbeet. Increased ethofumesate rates will lead to increased weed control, but even rates as low as 280 g ai ha^{-1} will provide some benefit with respect to weed control and herbicide resistance management. Greenhouse studies indicated that rates even lower than 280 g ha^{-1} could provide benefit in the form of increased retention of subsequently applied POST herbicides.

Although ethofumesate was the only residual herbicide used in this study, it is possible that similar results would be obtained when using other herbicides that inhibit VLCFA synthesis. Indeed, it was proposed over 45 yr ago that the thiocarbamate herbicide EPTC could be used at sublethal rates in order to allow greater control with subsequently applied POST herbicides (Gentner 1966). Intentional application of sublethal rates of ethofumesate is typically not recommended; however, the residual properties of ethofumesate will necessarily result in a sublethal concentration of the herbicide in the soil at some point after application. POST glyphosate applications will certainly provide the basis of any weed control program in glyphosate-resistant sugarbeet. Use of ethofumesate in glyphosate-resistant sugarbeet could be viewed, at least in part, as a way to increase the efficacy of POST applications, particularly on weed species (such as common lambsquarters) that are difficult to control with glyphosate. The rate of ethofumesate could be reduced to the point that crop injury potential is minimized, while still providing weed control benefit, even on late emerging weeds such as redroot pigweed and hairy nightshade.

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