Sugarbeet and Rotational Crop Tolerance from Ethofumesate 4SC Applied Postemergence

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ABSTRACT

Ethofumesate 4SC was approved in 2017 for postemergence application at rates up to 4.2 kg a.i. ha^{-1} on sugarbeet with more than two true leaves until 45 days before harvest. Ethofumesate 4SC postemergence at greater rates in mixtures with glyphosate may improve burndown control and increase soil residual control in sugarbeet of broadleaf weeds including waterhemp. Experiments were conducted in 2017, 2018, and 2019 in Michigan, Minnesota, and North Dakota, to determine sugarbeet crop tolerance and evaluate ethofumesate fate and persistence when application was timed to calendar dates representing 9-, 10-, and 11-month intervals between sugarbeet and crops commonly planted in sugarbeet rotations. Sugarbeet growth, root yield, sucrose content, and recoverable sucrose were not affected by ethofumesate rate or timing of ethofumesate application. Neither stand density, stature development, flowering date, and plant height nor grain yield, test weight, and moisture percentage of grain at physiological maturity of corn, dry bean, soybean, or wheat were affected by ethofumesate soil residues.

Additional Key words: *Beta vulgaris* L., preemergence, postemergence, herbicide

Abbreviations: ai = active ingredient, w = week, POST = postemergence, PHI = pre harvest interval

Ethofumesate is a selective herbicide commonly applied at 1.12 to 4.2 kg ai ha^{-1} for preplant and preemergence control of monocotyledonous and dicotyledonous weeds in sugarbeet (*Beta vulgaris* L.) (Dexter, 1975; Ekins and Cronin, 1972; Eshel et al., 1976; Sullivan and Fagala, 1970). Timely and adequate rainfall is required to achieve desired weed control since ethofumesate has low water solubility and is strongly adsorbed to soil (Shaner, 2014; Schweitzer, 1975). Ethofumesate is absorbed through emerging roots and shoots when soil-applied (Eshel et al., 1978).

Ethofumesate mode of action is inhibition of mitosis and reduced respiration and photosynthesis (Edwards et al., 2005). Several observations indicated ethofumesate also may affect surface waxes by inhibition of the biosynthesis of very long chain fatty acids (VLCFAs) although the specific mechanism of action is not fully understood (Abulnaja et al., 1992; Devine et al., 1993). Ethofumesate provides 10 w residual control to grass and broadleaf weed species (Ekins and Cronin, 1972).

Sugarbeet injury from ethofumesate soil-applied corresponds with herbicide rate and soil type (Schweizer, 1975). In Minnesota and eastern North Dakota, ethofumesate shows excellent sugarbeet tolerance at rates up to 4.5 kg ha^{-1} (Dexter, 1976). Commercial merit on prairie soils and full-season residual soil activity (Elkins and Cronin, 1972), especially on *Amaranthus* species (Schweizer, 1975) makes ethofumesate an excellent candidate for weed control in sugarbeet in Minnesota, eastern North Dakota and Michigan (Aaberg, 1981). However, ethofumesate fate and persistence must allow for rotational crop safety.

In Minnesota and North Dakota, monocotyledonous crops, including wheat (*Triticum aestivum* L.) and field corn (*Zea mays* L.) are important rotational crops with sugarbeet (Tanner, 1948, Jantzi et al., 2018). Ethofumesate residue injured wheat in 1976 when precipitation was below normal or totaled 178 mm, compared to the yearly average of 483 mm (D. Ritchison, 2019, personal communication) on fine textured soils prepared for small grains planting with shallow tillage (Schroeder and Dexter, 1979). Schroeder and Dexter (1979) reported wheat was more sensitive to ethofumesate residues than barley (*Hordeum vulgare* L.), or soybean (*Glycine max* L.) and shoot or seed exposure to ethofumesate-treated soil reduced emergence and fresh weight more than root exposure in both wheat and barley. Schweizer (1975) reported barley and wheat were roughly 10 times more susceptible to soil residues of ethofumesate than corn in greenhouse experiments. Other research reported barley and wheat density reduction and reduced vigor following broadcast ethofumesate application compared to band application on sugarbeet and when barley and wheat seedbed preparation followed superficial tillage on sugarbeet stubble compared with deep plowing (Schweizer, 1977). Finally, microbial activity, especially in warm and moist soil conditions, accounted for accelerated ethofumesate degradation compared to degradation in dry and cold soils (Schweizer, 1976; van Hoogstraten et al., 1974). Understanding more about the fate of ethofumesate in environmental conditions may allow for greater knowledge of carry-over injury to rotational crops.

The Ethofumesate 4SC label has expanded to include POST application alone and in mixtures from 0.42 to 4.2 kg ha^{-1} to sugarbeet with greater than two-true leaves and reduction of the preharvest interval (PHI) from 90 to 45 days (Anonymous, 2017). The revised Ethofumesate 4SC rates structure applied POST with glyphosate may provide both a second site of action for control of glyphosate sensitive weeds including common lambsquarters (*Chenopodium album* L.) and redroot pigweed (*Amaranthus retroflexus* L.), and improved control of glyphosate resistant weeds including kochia (*Bassia scoparia* (L.) A. J. Scott) and waterhemp [*Amaranthus tuberculatus* (moq.) J.D. Sauer] (Patzoldt et al., 2004). Little is known about postemergence activity and environmental fate from ethofumesate POST at rates greater than 0.38 kg ha^{-1}. Growers will need to consider the total amount of ethofumesate applied to sugarbeet, method and timing of application, as well as the method of seedbed preparation to accurately assess residues of weed control systems including soil applied and postemergence herbicides. The objective of this study was to a) evaluate sugarbeet tolerance from ethofumesate POST at rates to 4.48 kg ha^{-1} and b) demonstrate crops grown in sequence with sugarbeet including corn, dry bean (*Phaseolus vulgaris* L.), soybean, and wheat can tolerate residues from ethofumesate POST at greater rates in sugarbeet than were previously used.

MATERIALS AND METHODS

Field experiments were conducted near Crookston, Foxhome, and Lake Lillian, MN, Prosper, ND, and Richville, MI in 2017 and 2018 and repeated in Richville, MI in 2018 and 2019, totaling six environments evaluated. The sites represent the sugarbeet production area in Minnesota, eastern North Dakota, and Michigan. The data collected from these experiments could be readily implemented into weed management strategies in these three regions. Also, the Michigan location provided an additional rotational crop, dry bean, not evaluated in the other regions. In 2017, three identical experimental areas were seeded to sugarbeet approximately 3-cm deep after tillage. Planting dates ranged from mid-April in Michigan to early and mid-May in Minnesota and eastern North Dakota which are dates typical of sugarbeet production (Giles and Cattanach, 2004; Smith, 2003). Experiments were a randomized complete block design with six replications. Experiment details at each location can be found in Table 1 and 2. Precipitation data were collected from nearby weather stations operated by the North Dakota Agricultural Weather Network (NDAWN), Community Collaborative Rain, Snow and Hail Network (CoCoRaHS), the University of Minnesota Experiment Station, and the Michigan Automated Weather Network (MAWN) (Table 3).

Table 1. Sugarbeet hybrid, seeding date, seeding rate, and row spacing, across environments in 2017 and 2018.

Location	Planting Date	Sugarbeet Hybrid	Seeding Rate	Row Spacing
			--S/ha[§]--	cm
Prosper, ND	May 2, 2017	SV36271RR	149,435	56
Crookston, MN	May 3, 2017	BT80RR52	149,435	56
Foxhome, MN	May 12, 2017	HM4062	156,499	56
Lake Lillian, MN	May 6, 2017	BT9230	147,696	56
Richville, MI	April 18, 2017	HM9619RR	125,353	76
Richville, MI	April 30, 2018	CRG515	125,353	76

[§]Seeds per hectare.

Table 2. Soil texture, organic matter, and pH across environments in 2017 and 2018.

Location	Soil Texture	OM[§]	pH
		--%--	
Prosper, ND	Silt Loam	3.9	8.0
Crookston, MN	Sandy Loam	2.9	8.3
Foxhome, MN	Sandy Loam	2.5	7.4
Lake Lillian, MN	Loam	5.6	8.2
Richville, MI	Clay Loam	2.6	6.9
Richville, MI	Clay Loam	3.0	7.5

[§]Organic Matter.

Table 3. Annual precipitation 2017 to 2019 across environments.

Month	Prosper, ND 2017-2018	Crookston, MN 2017-2018	Foxhome, MN 2017-2018	Lake Lillian, MN 2017-2018	Richville, MI 2017-2018	Richville, MI 2018-2019
	------------------------------------	----------------------	----------------mm	----------------------	----------------------	------------------------------------
September	151.7	101.9	93.5	57.7	40.4	48.8
October	6.9	9.4	55.9	146.7	89.4	67.6
November	-	8.1	6.4	4.7	52.8	32.3
December	-	20.1	9.4	9.3	8.4	55.1
January	-	9.4	2.5	6.5	18.5	15.5
February	-	18.0	18.5	15.0	49.8	23.4
March	-	46.5	27.2	32.9	13.7	33.8
April	3.8	3.6	17.8	35.3	71.6	57.7
May	53.9	48.8	42.9	68.5	54.4	127.5
June	79.3	100.3	186.7	69.9	37.3	177.0
July	65.3	37.3	119.1	199.4	50.3	60.2
August	78.5	43.9	61.5	76.1	200.7	26.9
Total	439.4	447.3	641.4	722.0	687.3	725.8
Hist. Average§	425.5	475.3	547.4	760.4§§	661.0	661.0

§Historical Average = 10-year average.
§§9-year historical average.

Ethofumesate POST was timed to a calendar date in June, July, and August to simulate 11-, 10-, and 9-month crop rotation intervals, respectively, in addition to a sequential application timed approximately every two weeks. Ethofumesate rate, timing of application, and sugarbeet growth stage at application are listed in Table 4. Lake Lillian, MN did not receive the 10-month crop rotation interval treatment due to site constraints.

Table 4. Herbicide treatment, application rate, timing of application, and sugarbeet growth stage in 2017 and 2018.

Treatment§	Rate	Timing of Application	Sugarbeet Growth Stage
	kg ha^{-1}		Num of lvs
Untreated control	0		
Ethofumesate	1.12	Sequential§§	2/10/14/18
Ethofumesate	4.48	June 15	10
Ethofumesate	4.48	July 15	18
Ethofumesate	4.48	August 15	22

§High surfactant methylated oil concentrate (HSMOC) at 1.75 L ha^{-1} was applied with all treatments across locations.
§§Application of 1.12 kg ethofumesate ha^{-1} made every two weeks starting at the 2-lf sugarbeet stage until July 15.

Herbicides were applied with a bicycle wheel sprayer early in the season and a backpack sprayer later in the season in 159 L ha^{-1} spray solution through 8002 XR flat fan nozzles (TeeJet Technologies, Glendale Heights, IL) spaced 51 cm apart and pressurized with CO_2 at 345 kPa to all 6 rows of the 6-row plots on 56-cm spacing, 3.4 m x 10 m in length. Weeds, insects, and diseases were managed according to regional recommendations throughout the growing season.

Sugarbeet tolerance was evaluated by assessing visible sugarbeet injury following ethofumesate application. Visible stature reduction was observed 7 and 14 days (+/- 3 days) using a scale of 0 to 100 with a zero reflecting no reduction in above ground stature and a 100 reflecting complete reduction in above ground stature.

At harvest, sugarbeet were defoliated and harvested mechanically from the center two rows of each plot and weighed. A subsample was collected from each plot and analyzed for sucrose content and sugar loss to molasses (SLM). Root yield (kg ha^{-1}), purity (%), and recoverable sucrose (kg ha^{-1}) were calculated using the following calculations, respectively. Sugarbeet not harvested for yield assessment were removed from the experimental area to simulate harvest operations similar to a commercial field setting.

$$\text{Root yield (kg per hectare)} = \frac{\text{weight of harvested plot (kg)}}{\text{\% of hectare harvested}}$$

$$\text{Purity (\%)} = \left(100 - \left(\frac{\text{\% sugar loss to molasses}}{\text{\% sucrose content}}\right)\right) x\ 100$$

$$\text{Recoverable sucrose (kg per hectare)} = \left(\frac{((\text{\%purity} / 100)\ x\ \text{\%sucrose})}{100}\right) x \text{ root yield}$$

Plots were prepared for corn, dry bean, soybean, and wheat seeding in spring 2018 (all environments) and 2019 (Michigan environment only) using a field cultivator. Tillage was applied in the same direction as the previous herbicide treatments to incorporate fertilizer, prepare the seed bed, and ensure ethofumesate residue was not moved across plots. Experiment details follow for corn and wheat in Table 5 and dry bean and soybean in Table 6. Weeds, insects, and diseases were managed throughout the 2018 and 2019 growing seasons.

Stand per unit area was counted and percent stature reduction was evaluated visually on May 29, June 9, and June 20, 2018 at Prosper; June 5, June 14, June 25, and July 9, 2018 at Crookston; May 31 at Foxhome, MN; May 31, June 14, and July 12, 2018 at Lake Lillian; May 31, June 15, June 29, July 16, July 17, and August 14 at Richville in 2018; and June 7, July 8, and July 19 at Richville in 2019. Evaluations were a visual estimate of percentage injury ranging from 0% (no injury) to 100% (all plants completely eliminated). Stand density was determined at first evaluation by counting plants along 3 m transects in the middle two rows in each plot in MN and ND. Richville, MI collected 9 m counts. Plant height was measured at the last evaluation by averaging five random samples throughout the plot. Grain weight was collected mechanically at physiological maturity from the center three rows of plots or from an area 1.5 m by the length of plot. Moisture and test weight were determined from grain weight (DICKEY-john, Auburn IL, 62615) and corn, dry bean, soybean, and wheat grain yield are reported at 15.5%, 13%, 13% and 13.5% moisture content, respectively.

Data from the field experiment were analyzed using the MIXED (method=type3) procedure in SAS Data Management Software 9.4 (SAS Institute Inc., SAS Campus Drive, Cary, North Carolina 27513, USA). Environment and replicate were considered random effects while treatments were fixed effects. Each crop was considered a different experiment. If F-test was significant at $P \leq 0.05$, mean separation was performed using least square means paired differences. Significantly different treatment means were separated using t-test when data was found to be significantly different at a significance level of P=0.05.

Table 5. Corn and wheat seeding date, variety, and seeding rate for locations in 2018 and Richville in 2019.

	Wheat			Corn		
Location	Planting Date	Variety	Planting Rate	Planting Date	Variety	Planting Rate
			kg/ha§			--S/ha§§--
Prosper	May 14, 2018	‘Prosper’	183	May 14, 2018	DKC45-64RR2	76,570
Crookston	May 15, 2018	‘Prosper’	183	May 16, 2018	DKC45-64RR2	76,570
Foxhome	May 15, 2018	‘Prosper’	183	May 15, 2018	DKC45-64RR2	76,570
Lake Lillian	May 15, 2018	‘Prosper’	183	May 15, 2018	DKC45-64RR2	76,570
Richville	N/A§§§	N/A	N/A	May 1, 2018	Stine 9316	79,040
Richville	N/A	N/A	N/A	May 2019	Stine 9202	79,040

§Kilograms per hectare.
§§Seeds per hectare.
§§§Wheat crop not evaluated in Richville, MI.

Table 6. Dry bean and soybean seeding date, variety, and seeding rate for locations in 2018 and Richville in 2019.

	Soybean			Dry Bean		
Location	Planting Date	Variety	Planting Rate	Planting Date	Variety	Planting Rate
			--S/ha§--			--S/ha--
Prosper	May 14, 2018	AG0934RR2	370,500	N/A§§	N/A	N/A
Crookston	May 16, 2018	AG0934RR2	370,500	N/A	N/A	N/A
Foxhome	May 15, 2018	AG0934RR2	370,500	N/A	N/A	N/A
Lake Lillian	May 15, 2018	AG11X8	370,500	N/A	N/A	N/A
Richville	May 16, 2018	Stine 14RD62	370,500	June 19, 2018	Zenith	261,820
Richville	May 7, 2019	Stine 13GA62	370,500	June 19, 2019	Zenith	261,820

§Seeds per hectare.
§§Dry bean crop only evaluated in Richville, MI.

RESULTS

Sugarbeet Results

Sugarbeet injury reported as chlorosis or stature reduction was negligible across ethofumesate treatment at any location throughout the growing season in 2017 and 2018 (data not presented). Herbicide treatment did not affect root yield in any environment (Table 7). Sucrose content was greater (p=0.0010) when 1.12 kg ethofumesate ha^{-1} was applied at the 2-lf stage and repeated three times on approximately 14 day intervals (sequence) or when 4.48 kg ethofumesate ha^{-1} was applied June 15 (11-month interval) compared with the untreated control or 4.48 kg ethofumesate ha^{-1} applied August 15 (9-month interval) at Foxhome, MN. Harvest data from Prosper, ND or Richville, MI (in 2017 or 2018) were not included in the analysis due to emergence issues and resultant site variability related to weather conditions at planting.

Rotational Crop Results

Dry bean, soybean, and wheat density and stature were not affected by residues from ethofumesate (Figures 1 and 2), however, corn stature was reduced (p=0.0160) from both the sequential application and 4.48 kg ethofumesate ha^{-1} applied in July (Figure 2).

Corn yield components were not negatively affected by ethofumesate rate and application timing (Table 8). However, grain yield was numerically less when corn was seeded after sequential applications of 1.12 kg ethofumesate ha^{-1} or 11-months after a single 4.48 kg ethofumesate ha^{-1} application compared to the untreated control or 9- or 10-months after a single 4.48 kg ethofumesate ha^{-1} application. Additionally, corn height at harvest was the same across ethofumesate applications (data not presented). Corn yield from Crookston, MN was not included in the combined location analysis due to damage from hail in June. Corn yield at Crookston averaged approximately 9,000 kg ha^{-1} across treatments or 4,500 kg ha^{-1} less than the other locations. Corn grain moisture was affected by herbicide treatment in Richville, MI (Figure 3). Corn grain averaged 15.7% moisture following a 10- or 9-month interval between application and seeding compared with 16.5% in the untreated control plots when analyzed singly.

Dry bean did not display any growth or developmental effects from ethofumesate throughout either growing season at Richville, MI (data not presented). Grain yield in the untreated check and dry bean seeded 9-months after 4.48 kg ethofumesate ha^{-1} application was numerically less than (p=0.6924) yield following dry bean seeded 10- or 11-months after ethofumesate application across years. Moisture and yield, when averaged across treatment, were 16% and 1,500 kg ha^{-1}, respectively.

Soybean yield was not affected by ethofumesate rate or 9-, 10-, or 11-month interval between ethofumesate application and seeding across locations (Table 9). Soybean yield data from Crookston, MN and Prosper, ND were evaluated separately due to hail in June and September,

Table 7. Sugarbeet root yield, recoverable sucrose, and sucrose content in response to timing of ethofumesate application, across environments in 2017.

	Crookston, MN			Foxhome, MN			Lake Lillian, MN		
Treatment[§]	Root Yield[§§]	Rec. Suc.[§§§]	Sucrose Content	Root Yield	Rec. Suc.	Sucrose Content	Root Yield	Rec. Suc.	Sucrose Content
	Mg/ha	-kg/ha-	--%--	Mg/ha	-kg/ha-	--%--	Mg/ha	-kg/ha-	--%--
Untreated Control	62.1	10,945	18.5	52.0	6,297	14.4 b	78.9	11,283	16.8
Sequential	62.8	10,974	18.5	50.2	6,293	14.8 a	78.7	11,431	16.8
11-Month Interval	63.4	11,089	18.4	50.0	6,340	14.9 a	78.0	11,168	16.6
10-Month Interval	63.2	11,040	18.4	50.7	6,284	14.6 ab	-	-	-
9-Month Interval	61.7	10,741	18.4	50.7	6,182	14.3 b	80.9	11,623	16.7
p value	0.8144	0.8001	0.7295	0.5268	0.9225	0.0010	0.1753	0.1713	0.6291

[§]Ethofumesate was applied at the rates given and at the timings referenced in Table 1.
[§§]Root yield reported in megagram (Mg) ha-1. One Mg = 1000 kg = one metric ton.
[§§§]Recoverable sucrose reported in kilogram per hectare.

Table 8. Ethofumesate sugarbeet crop residue impact on corn yield in 2018 and 2019.

	Prosper, ND, Foxhome, MN, Lake Lillian, MN, Richville, MI			Crookston, MN		
Treatment[§]	Test Weight	Moisture	Grain Yield	Test Weight	Moisture	Grain Yield
	kg/hL[§§]	--%--	kg/ha[§§§]	kg/hL	--%--	-kg/ha-
Untreated Control	69.1	18.9	13,450	77.1	15.5	8,580
Sequential	68.8	19.0	13,380	78.3	16.5	9,428
11-Month Interval	69.3	18.9	13,180	77.0	15.6	9,798
10-Month Interval	69.0	18.9	13,650	77.3	15.2	8,599
9-Month Interval	69.5	18.8	14,120	78.3	16.1	8,580
p value	0.5044	0.9865	0.1452	0.6547	0.5207	0.7787

[§]Ethofumesate was applied at the rates given and at the timings referenced in Table 1.
[§§]kilogram per hectoliter
[§§§]kilogram per hectare

Table 9. Ethofumesate crop residue impact on soybean yield in 2018 and 2019.

	Foxhome, MN; Lake Lillian, MN; Richville, MI			Prosper, ND; Crookston, MN		
Treatment[§]	Test Weight	Moisture	Grain Yield	Test Weight	Moisture	Grain Yield
	--kg/hL[§§]--	--%--	--kg/ha[§§§]--	--kg/hL--	--%--	--kg/ha--
Untreated Control	67.9	13.6	4,040	69.3	13.6	2,560
Sequential	67.3	13.4	4,100	68.5	13.6	2,560
11-Month Interval	67.8	13.4	4,040	68.0	13.6	2,480
10-Month Interval	67.6	13.4	3,970	68.3	13.6	2,630
9-Month Interval	69.0	13.5	4,240	68.5	13.5	2,460
p value	0.0896	0.5006	0.1603	0.3114	0.6116	0.6102

[§]Ethofumesate was applied at the rates given and at the timings referenced in Table 1.
[§§]kilogram per hectoliter
[§§§]kilogram per hectare

respectively, which decreased the yield by approximately 1,500 kg ha^{-1}.

Wheat yield components were not affected by ethofumesate rate or interval between ethofumesate application and wheat seeding date (Figure 4). Difference in wheat grain yield between ethofumesate treatment (rate and application timing) and untreated check were plotted across environments since previous research indicated soil type and rainfall affected ethofumesate fate and persistence in soil (Schroeder and Dexter, 1979; Schweizer, 1976) (Figure 5). More treatment variability in wheat grain yield was observed at the Foxhome, MN location than at the other locations.

Rainfall at Foxhome, MN was greater than rainfall at Crookston, MN and Prosper, ND but was less than rainfall at Lake Lillian, MN (Table 3). Sandy loam texture and low organic matter content presumably should have increased ethofumesate mobility and decreased half-life compared to the higher organic matter soil at Crookston, resulting in less ethofumesate residue at Foxhome compared to Prosper or Crookston.

Figure 1. Corn (p=0.3399), dry bean (p=0.7391), soybean (p=0.8933) and wheat (p=0.3377) stand density in response to timing of ethofumesate application and rate, across environments in 2018 and 2019. Treatment rates and timings referenced in Table 1.

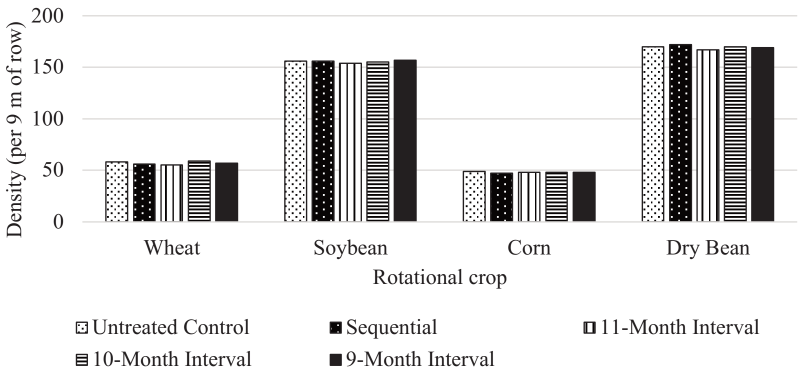


Figure 2. Corn (p=0.0160), dry bean (p=1), soybean (0.2611) and wheat (p=0.8979) visible percent stature reduction in response to timing of ethofumesate application and rate, across environments in 2018 and 2019. Means within a main effect not sharing any letter were significantly different by the t-test at the 95% level of significance. Treatment rates and timings referenced in Table 1.

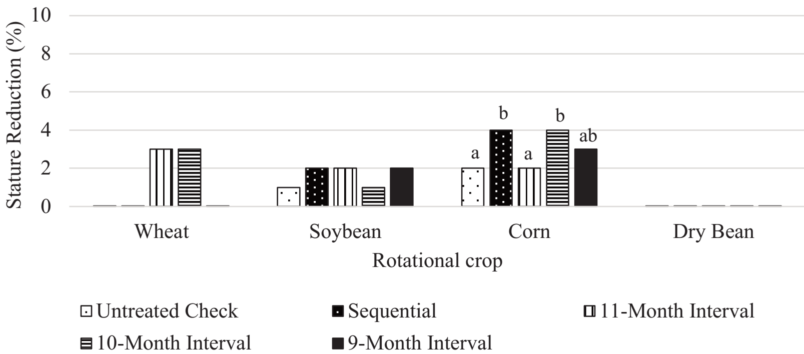


Figure 3. Response of corn percent moisture to ethofumesate residues, Richville MI, 2018. Means within a main effect not sharing any letter were significantly different by the t-test at the 95% level of significance. Treatment rates and timings referenced in Table 1.

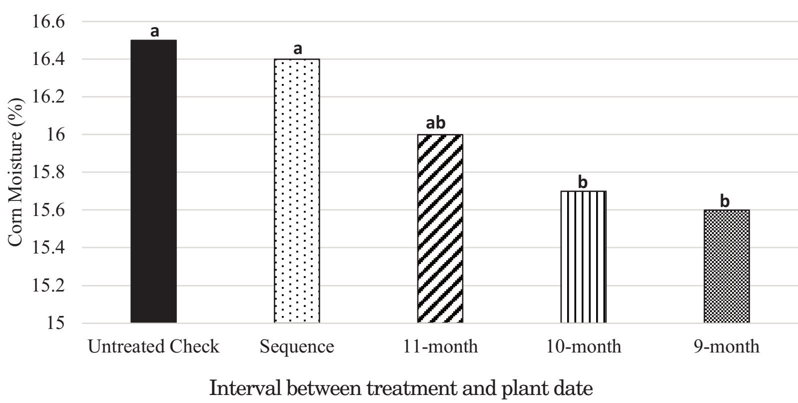


Figure 4. Wheat yield (p=0.6675), moisture (p=0.6729) and test weight (p=0.4080) in response to 2017 ethofumesate rate and timing of ethofumesate application, averaged across environments, 2018. Treatment rates and timings referenced in Table 1.

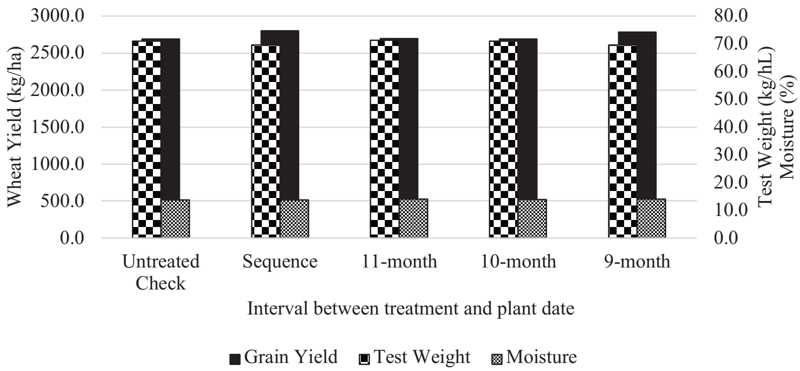
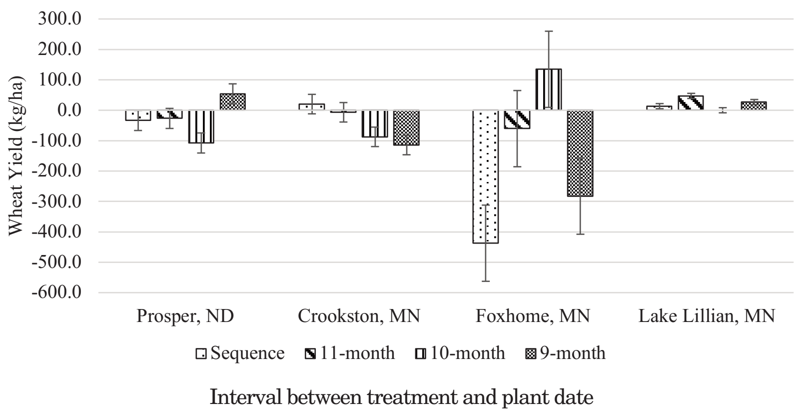


Figure 5. Wheat grain yield (p=0.6675) difference (untreated check – treatment) and standard error of the mean (error bars), across environments, 2018. Treatment rates and timings referenced in Table 1.



DISCUSSION

Loss of wheat grain yield was reported in field research (Schroeder and Dexter, 1979) and wheat and barley stature reduction was reported in commercial fields (personal communication with T. Grove, American Crystal Sugar Company) following 1.12 to 3.36 kg ethofumesate ha^{-1} applied in the previous year. In our experiments, 4.48 kg ethofumesate ha^{-1} in a single application or total ethofumesate following sequential applications applied in June, July, and August did not reduce corn, dry bean, soybean, or wheat stand density, cause stature reduction, or reduce grain yield compared with the untreated control. Moreover, grain moisture at harvest was less in treatments where corn was seeded 9- or 10-months following ethofumesate application in sugarbeet as compared to the untreated check or corn seeded after sequential ethofumesate applications or corn seeded 11-month after ethofumesate at Richville, MI in 2018. Less grain moisture at maturity is opposite of what one might expect since pesticides may delay maturation and increase grain moisture content at harvest in some environments (Burnside and Wicks, 1965; Dwyer et al., 1994; Ma and Subedi, 2005).

Ethofumesate residues affecting growth and development of rotational crops, in Minnesota and eastern North Dakota, often are associated with lack of precipitation (either rainfall or winter snowfall) and soil temperature following ethofumesate application and rate of ethofumesate applied (Schweizer, 1975; Schweizer, 1976). Precipitation was near normal or above normal across our locations in 2017, 2018, and 2019 (Table 3) which could have aided in the degradation of residual ethofumesate.

Degradation of ethofumesate in soil is related to the action of soil microorganisms and is accelerated in warm and moist soils as compared with dry and cold soils. (van Hoogstraten et al., 1974; Schweitzer, 1976). Ethofumesate controls susceptible weeds species for as long as 10 w (Ekins and Cronin, 1972) and has a half-life in a sandy loam or a loam soil of 7.7 or 12.6 w, respectively (Schweitzer, 1976). However, ethofumesate was applied preplant or preemergence to bare soil in previous experiments, as opposed to our experiment where ethofumesate was applied postemergence to sugarbeet from 2- to 22-leaves. This can affect responses as Gardner and Branham (2001) observed with the fate of ethofumesate when applied POST to turfgrass versus over bare soil. They reported the half-life of ethofumesate was 3 days on turf compared to 51 days on bare soil. The authors attributed shorter half-life to increased microbial activity in turfgrass thatch resulting in greater ethofumesate degradation before it moved into the soil. Likewise, Wang et al. (2005) reported degradation of soil-applied ethofumesate was significantly slower than degradation by plant metabolism.

Ethofumesate loss and/or degradation might be a combination of multiple factors including microbial, chemical, uptake by plants, and leaching following POST application (McAuliffe and Appleby, 1984).

McAuliffe and Appleby (1984) reported under dry conditions at application (<2.5% water), chemical degradation and strong adsorption may reduce ethofumesate activity. Our experiment was not designed to account for losses of applied ethofumesate but rather was designed to determine if ethofumesate residues were harmful to rotational crops. Future research should investigate fate of ethofumesate applied POST, especially if the new labeled uses for ethofumesate are adopted by growers.

CONCLUSION

Previous experiments reported ethofumesate residue injuring rotational crops, especially wheat and barley (Schweizer, 1975; Schroeder and Dexter, 1979). Ethofumesate applied POST at rates to 4.48 kg ha^{-1} from the 2- to 22-sugarbeet leaf stage did not injure monocotyledonous crops including wheat and corn planted in sequence with sugarbeet in our experiments. However, crop residue at application in previous experiments was different from our experiment. Ethofumesate was applied to bare soil in the Schroeder and Dexter (1979) and Schweizer (1975, 1976, 1977) experiments, whereas ethofumesate was applied POST over a sugarbeet canopy in our experiments. In addition, our experiments received average or above average precipitation, which presumably increased microbial activity and decreased ethofumesate soil persistence (van Hoogstraten et al., 1974; Schweitzer, 1976).

The value of a soil residual sugarbeet herbicide treatment in a weed management system is a combination of its effectiveness to control broad spectrum annual weeds during the growing season and its degradation to non-phytotoxic residues in sugarbeet and soil prior to harvest and seeding of the rotational crop. A suitable herbicide is one that is adsorbed to soils and remains near the soil surface through row closure but does not accumulate in sugarbeet or persist in the soil and affect crops planted in sequence with sugarbeet. Ethofumesate applied POST at rates to 4.48 kg ha^{-1} did not damage sugarbeet and did not affect yield of crops grown in sequence with sugarbeet in experiments conducted across six environments in Michigan, Minnesota, and North Dakota in 2018 and 2019.

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