ETHOFUMESATE 4SC APPLIED POSTEMERGENCE IN SUGARBEET

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Alexa Lynn Lystad

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

SUPERVISORY COMMITTEE:

Dr. Thomas J. Peters
Chair

Dr. Kirk Howatt

Dr. Marisol Berti

Dr. Christy Sprague

Approved:

03/10/2020
Date

Dr. Richard D. Horsley
Department Chair

ABSTRACT

Experiments evaluated sugarbeet tolerance, herbicide efficacy on common lambsquarters (*Chenopodium album* L.), redroot pigweed (*Amaranthus retroflexus* L.) and waterhemp (*Amaranthus tuberculatus* (moq.) J.D. Sauer), and rotational crop safety to ethofumesate (2-Ethoxy-2,3-dihydro-3,3-dimethyl-5-benzofuranol methanesulfonate) in 2017, 2018, and 2019. Ethofumesate applied at 2.24 or 4.48 kg ha^{-1} at the sugarbeet two-true leaf stage reduced sugarbeet stature and recoverable sucrose in field experiments. Ethofumesate at 1.12 kg ha^{-1} plus glyphosate at 1.26 kg ha^{-1} applied preemergence (PRE) or early postemergence (EPOST) to 1.3-cm weeds provided broad spectrum control with the least sugarbeet stature reduction in field and greenhouse experiments. Corn (*Zea mays* L.), dry bean *(Phaseolus vulgaris* L.), soybean (*Glycine max* L.), and wheat *(Triticum aestivum* L.) stand density, stature reduction, flowering date, grain yield, test weight, and grain moisture were not affected by 4.48 kg ha^{-1} ethofumesate applied at calendar dates representing 9-, 10-, and 11-month intervals between sugarbeet and rotational crops.

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CHAPTER 1. REVIEW OF LITERATURE

The modern sugarbeet (*Beta vulgaris* L.) originated from central Europe in the early nineteenth century (Cooke and Scott 1993). The distribution of sugarbeet has since expanded around the world and is produced in all populated continents, except Australia. Sugarbeet is the second main source of sucrose or sugar; sugarcane being the first. Sucrose has been valued in the human diet for thousands of years (Cooke and Scott 1993). Increased competition from other sugars, such as high fructose corn syrup, and artificial sweeteners, such as aspartame, has not had a negative impact on sucrose demand.

World sucrose production had increased about 37% from 1980 to 1990 (Cooke and Scott 1993). World production is more than 130 million metric tons of sucrose and about 35% is from beet sucrose (Harveson 2017). France, United States, and Germany are the most important growers of sugarbeet, each producing over 25 million tons annually (Oerke and Dehne 2004).

Growth in sugarbeet production could be related to an increased capacity among sugarbeet factories (Ali 2004). Sugarbeet-producing states consist of Michigan (Great Lakes Region); Minnesota and North Dakota (Red River Valley Region); Wyoming, Montana, Colorado, and Nebraska (Great Plains Region); Idaho, Oregon, and Washington (Northwest Region); and California (Southwest Region). Beet-sugar processing factories in the United States are conveniently located near production areas to reduce transportation costs and deterioration of sucrose content in harvested sugarbeet. The Red River Valley region is the largest sugarbeet growing region in the Unites States (Ali 2004) with about 458,000 hectares (ha) planted in 2019 (National Agricultural Statistics Service 2019).

Sugarbeet is in the Amaranthaceae family under the subfamily Betoidae (Muller and Borsch 2005). It is a biennial plant harvested before winter frost for sucrose production in the

United States (Elliott and Weston 1993). Sugarbeet grows most successfully in cool-weather areas, however, can adapt to many soil and climatic conditions (Ali 2004).

Sugarbeet is harvested for the root (Ali 2004), which is the storage organ of the plant (Elliott and Weston 1993). Sugarbeet growth was originally divided into three phases: 1) shoot growth; 2) storage root growth; and 3) sucrose storage (Milford 2006). However, later discoveries of overlapping phases suggested a more continuous development. In general, leaf canopy development is dominant in early spring and shifts to storage root growth and sucrose accumulation in late summer to fall in North Dakota.

The amount of extracted raw sucrose was about 4% after processing in 1801 (Francis 2006). Certain varieties began to carry 11% to 13% sucrose content due to increased breeding and selection efforts. Today, fresh and dry weight concentration of sucrose in the roots are about 18% and 75%, respectively (Elliott and Weston 1993). The lower part of the root contains the lowest concentration of sucrose and gradually increases from the lower- to mid- crown region of the sugarbeet root, respectively (Hoffmann and Märländer 2016). Sucrose content decreases near the top of the crown. In general, the sucrose concentration is greatest at the widest circumference of the sugarbeet root.

Sugarbeet is mainly used for sucrose but byproducts of sucrose production include pulp, molasses, and fiber, which are used for feed (Environment Directorate 2001). Sugarbeet is highly sensitive to pests such as weeds and must be monitored closely throughout the growing season to maintain control of these problems (Ali 2004).

Weed control is one of the youngest sciences but a relatively old art according to Timmons (1970). Primary weed control consisted of mechanical methods such as cultivator, rotary hoe, and hand weeding in the 1940s (Schweizer and Dexter 1987). Chemical weed control treatments usually were inorganic chemicals such as sodium and potassium chloride until the late 1940s when organic chemicals began to be evaluated. There was a three-fold increase from 25 to 120 herbicides after 1950.

Weeds are responsible for about 50% yield loss in sugarbeet (Oerke and Dehne 2004). Uncontrolled, interference from annual weeds can completely suppress the sugarbeet crop (Schweizer and Dexter 1987). This equates to about $211 and $369 million in loss of income for sugarbeet production in North Dakota and Minnesota, respectively (Soltani et al. 2018). A sparse, moderate, and severe infestation can result in 10%, 24%, and 43% to 90% yield loss, respectively. Weed control practices safeguard more than 56% of potential sugarbeet production, which equates to 199 million tons, from yield reduction.

Weeds create competition for resources (Brimhall et al. 1965) and reduce sugarbeet stands early in the growing season (Chitband et al. 2014). Annual broadleaf weeds are more competitive than annual grasses and often grow two to three times taller than sugarbeet by mid-summer (Schweizer and May 1993). Sugarbeet is a poor competitor with weeds from emergence to canopy closure (Cattanach et al. 1991). Young sugarbeet plants are small, lack vigor, and take roughly two months to shade the ground, providing an ample time period for weeds to establish and compete.

Weeds compete for light, nutrients, and water which causes crop failure if not controlled (Cioni and Maines 2011). Annual weeds are great competitors because of their ability to grow above multiple crop canopies, shading of desired crops, and have similar emergence patterns to annual crops. Uncontrolled annual weeds emerging within eight weeks of planting or within four weeks of sugarbeet reaching the two-leaf stage could reduce root yields by 26% to 100% (Chitband et al. 2014).

Common lambsquarters (*Chenopodium album* L.) is a troublesome weed that reduces yield and recoverable sucrose content in sugarbeet (Schweizer 1983). Common lambsquarters has confirmed triazine and ALS-resistant biotypes with only suspected glyphosate-resistant biotypes (Heap 2020). Wicks and Wilson (1983) reported common lambsquarters biomass was responsible for 86% of the variability in sugarbeet yields when left uncontrolled.

Common lambsquarters is a summer annual in the Chenopodiaceae family (Heap 2020) that can emerge over an extended period but has primary emergence in mid- to late spring (Curran et al. 2007). An average plant produces more than 70,000 seeds. Seed dormancy in common lambsquarters contributes to its success as a weed and allows viability for several decades. Conn et al. (2006) reported three percent of common lambsquarters seed remained viable after 19.7 years. Optimum seed depth for emergence is 0.25-cm and very few seedlings emerge from 2.5-cm or deeper. Common lambsquarters is self-pollinated but wind can result in some cross-pollination.

Redroot pigweed (*Amaranthus retroflexus* L.) is another troublesome weed in sugarbeet production areas (Schweizer and Dexter 1987). Redroot pigweed is an erect, branching summer annual in the Amaranthaceae family (Heap 2020) that can reach heights of 1- to 2-m (Schonbeck 2015). Stems and leaves may be covered with fine hairs. Leaves are egg-shaped with leaf blades that taper to rounded or pointed tips. The distinct red or pink taproot and lower stem for which this weed was named, is a key characteristic, however, many other *Amaranthus* species show similar coloration.

Redroot pigweed has a monecious reproductive system with separate male and female flowers on the same plant and can produce between 230,000 and 500,000 seeds (Invasive Species Compendium 2020). Optimum emergence depth is about 1-cm. Favorable growing environments for redroot pigweed includes high light intensity and temperatures. Redroot pigweed reduces yield by allelopathic effects on both weeds and crops, hosting crop pests and diseases, and competing for resources (Invasive Species Compendium 2020).

A relative of redroot pigweed, which is considered a major troublesome weed in sugarbeet production areas is waterhemp (*Amaranthus tuberculatus* (moq.) J.D. Sauer). Waterhemp is a summer annual in the Amaranthaceae family (Heap 2020) that can grow up to 2.5-cm a day (Nordby et al. 2007). Height can range from 10-cm to 4-m tall but is typically 1- to 1.5-m tall in a production field setting.

Waterhemp is a dioecious species which forces cross-pollination (Nordby et al. 2007). Waterhemp can produce >2 million seeds per plant in optimal conditions (Hartzler et al. 2004). Seeds are very small, dark in color, and can germinate at very shallow depths (≤1-cm) (Nordby et al. 2007).

A key characteristic of waterhemp includes late summer emergence (Hartzler et al. 1999). Waterhemp has a longer germination period than other grass and broadleaf species, especially following rainfall. The delayed and extended emergence period benefits the weed species in weed management systems, especially those not using a residual herbicide or late season weed control.

Ethofumesate (2-Ethoxy-2,3-dihydro-3,3-dimethyl-5-benzofuranol methanesulfonate) is a herbicide used to control common lambsquarters, waterhemp, and redroot pigweed in sugarbeet production (Ekins and Cronin 1972). Ethofumesate was first registered by Fisons Corporation as ‘Nortron’ in 1977 (Edwards et al. 2005) and is a selective herbicide registered for preplant, preemergence, and postemergence use to control grasses and broadleaf weeds in sugarbeet.

Original use rates range from 1.12 kg to 4.2 kg active ingredient (ai) ha^{-1} per season (Kellogg 2011).

Ethofumesate mode of action includes inhibition of mitosis along with reduced respiration and photosynthesis (Edwards et al. 2005). Robert et al. (1978) reported preplant-incorporated ethofumesate significantly reduced the amount of epicuticular wax on the surface of cabbage (*Brassica oleracea var. capitata* L.) leaves. The authors observed ethofumesate inhibited chain elongation of fatty acids in the elongation-decarboxylation pathway of epicuticular wax synthesis, allowing a longer retention time of other herbicides on weeds. They concluded ethofumesate appeared to be a more potent inhibitor of epicuticular wax deposition than EPTC (S-Ethyl dipropylthiocarbamate).

Ethofumesate provides up to 10 weeks of residual control to grass and broadleaf weed species (Ekins and Cronin 1972). Ethofumesate is absorbed through emerging roots and shoots when applied to soil (Eshel et al. 1978). Ethofumesate rarely leaches in the soil profile due to low water solubility and high soil adsorption characteristics (Shaner 2014; Schweitzer 1975). Therefore, soil-applied ethofumesate usually remains in the sugarbeet hypocotyl zone of the soil with very little leaching to the root zone (Eshel et al. 1978). Foliar applications to two-leaf sugarbeet had rapid translocation around the treated area, but no translocation out of the treated leaf.

Several observations conclude that this herbicide may affect surface waxes (Abulnaja et al. 1992). Eshel et al. (1976) reported a synergistic effect following foliar application of mixtures of ethofumesate and desmedipham. They noted negligible sugarbeet growth reduction when ethofumesate was applied alone. Desmedipham alone resulted in 39% sugarbeet growth reduction. The interaction of the mixture increased desmedipham activity which resulted in increased sugarbeet injury.

Glyphosate (N-(phosphonomethyl) glycine) is an important sugarbeet herbicide (Kniss et al. 2004). Glyphosate registration was issued in 1974 (National Pesticide Information Center 2019), however, was not available for use in glyphosate-resistant varieties of sugarbeet until 2008 (Morishita 2018). Glyphosate is a herbicide used in many food and non-food crops and non-crop areas where non-selective control of all weeds is desired. Glyphosate site of action is inhibition of 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) (Shaner 2006). This biosynthetic pathway is necessary to produce the aromatic amino acids, auxin, phytoalexins, folic acid, lignin, plastoquinones, and many other secondary products.

Glyphosate provides control of many grasses and broadleaf weeds but does not have any residual weed control activity (Schweizer 1975). Glyphosate alone fails to control species with resistant alleles (Baylis 2000) or provide residual soil activity (Schweizer 1975). Species with resistant alleles, or herbicide resistance, can be due to factors such as reduced herbicide absorption, detoxification of the herbicide through metabolism, or alteration of binding site (Koger and Reddy 2005).

Ferreira and Reddy (2000) reported decreased absorption of glyphosate in Amazonian coca (*Erythroxylum coca var. ipadu)* compared with Columbian coca (*E. novogranatense var. novogranatense)*. Autoradiography showed similar translocation patterns, however, glyphosate absorption with *E. coca* young and mature plants was 1.3 and 3.6 times less, respectively, than *E. novogranatense* after treatment. Ferreira and Reddy (2000) demonstrated thickness, chemical composition, or ultrastructure of epicuticular waxes (Holloway 1970) can have an adverse effect on glyphosate absorption. The combination of ethofumesate depleting epicuticular waxes of some species (Robert et al. 1978) with increased absorption and translocation (Ferreira and Reddy 2000) make the mixture of the two herbicides reasonable.

Kniss and Odero (2013) reported on the interaction between preemergence (PRE) ethofumesate and postemergence (POST) glyphosate. Their hypothesis was preemergence ethofumesate would increase POST spray retention and weed control with glyphosate. They found common lambsquarters and redroot pigweed control improved as ethofumesate PRE rate increased, however, improved glyphosate retention was not observed when glyphosate or glyphosate mixtures with ethofumesate followed ethofumesate PRE.

Peters and Lystad (2017) reported 100% waterhemp control from glyphosate and ethofumesate mixtures. They reported ethofumesate POST suppressed but did not control emerged broadleaf weeds; however, ethofumesate mixtures improved season long control compared with glyphosate alone.

Ethofumesate PRE provides excellent sugarbeet tolerance at rates to 4.5 kg ha^{-1} in Minnesota and eastern North Dakota (Dexter 1976). Sustained performance 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 and eastern North Dakota and Michigan (Aaberg 1981). However, ethofumesate fate and persistence must allow for rotational crop safety.

Monocotyledonous crops, including wheat (*Triticum aestivum* L.) and field corn (*Zea mays* L.), are important rotational crops with sugarbeet in Minnesota and North Dakota (Tanner 1948, Jantzi et al. 2018). Ethofumesate residues injured wheat when rainfall 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 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. Moreover, other research reported greater barley and wheat stand density reduction and reduced vigor following broadcast ethofumesate application compared with band application on sugarbeet and when barley and wheat seeding 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 with degradation in dry and cold soils (Schweizer 1976; van Hoogstraten et al. 1974).

Generic Crop Science (Generic Crop Science LLC., Henderson, NV), in collaboration with the Beet Sugar Development Foundation, developed a new label for ethofumesate, Ethofumesate 4SC, by increasing use rates from 0.38 to 4.48 kg ha^{-1} postemergence to sugarbeet greater than two-true leaves and decreasing the pre-harvest interval (PHI) from 90 to 45 days (Anonymous 2017). Increased rates of ethofumesate POST may provide extended residual control of late-emerging weed species, such as waterhemp, and add a second site of action to POST glyphosate applications which could improve control of herbicide-resistant weeds (Patzoldt et al. 2004).

Peters and Lystad (2017) evaluated split-applications of ethofumesate POST at 2.24 kg ha^{-1}. They reported ethofumesate was not a stand-alone postemergence herbicide for common lambsquarters, however, observed activity on the young tissue of weed species, especially in the meristem region (T. Peters 2018, personal communication). The concentration of ethofumesate in meristem regions could reduce seed production by affecting reproductive development. Eshel et al. (1978) reported a similar observation of ethofumesate translocating to the edges of the treated leaves; however, ethofumesate did not affect new leaves. These results suggest ethofumesate POST may not be used as a stand-alone herbicide, however, could provide beneficial developmental compromises to emerged weed species.

Preemergence herbicide use decreased to less than 5% of arable cropland in North Dakota and Minnesota in the mid-1980s (Dale et al. 2006). Sugarbeet growers elected to focus on POST herbicides since Minnesota and North Dakota soils required higher use rates of soil-applied herbicides which were costlier than POST herbicide applications. Furthermore, soil-applied herbicide performance was adversely affected by inconsistent rainfall to activate herbicides (Dale et al. 2006).

Dale et al. (2006) examined whether preemergence herbicides were necessary for weed control in sugarbeet and if they increased sugarbeet injury. The researchers reported climatic conditions had an important impact on crop safety and weed efficacy. For example, more damage in sugarbeet was observed during the cool, wet year than in the drier year. They concluded both preemergence and postemergence applications applied in a weed management system were effective in wet springs. They did not observe significant sugarbeet injury from ethofumesate applied preemergence.

The practice of applying soil-applied herbicides POST in production settings could result in lasting residual herbicide later in the growing season. The lack of injury from ethofumesate applied pre- and postemergence at the previous label rates, along with additive effects reported from other studies, suggests potential improved herbicide efficacy with increased rates of ethofumesate.

Herbicide mixtures often create challenges with sugarbeet crop safety. Mixtures may create an additive effect improving weed control but also causing too much crop injury; therefore, the herbicide program would not be utilized or feasible in a production setting due to crop damage. Increasing the rate of ethofumesate will not be beneficial or worth the risk of crop injury if all rates and mixtures do not provide acceptable weed control. Second, there is a concern for ethofumesate fate and persistence which could not allow for rotational crop safety.

The purpose of this research was to evaluate ethofumesate at rates to 4.48 kg ha^{-1} postemergence in sugarbeet. The objectives of the research are, to a) determine if ethofumesate postemergence alone or in mixtures at greater rates increases sugarbeet injury; b) evaluate common lambsquarters, redroot pigweed, and waterhemp control with ethofumesate postemergence at rates up to 4.48 kg ha^{-1}; c) determine if tank mixtures with ethofumesate at greater rates improve broadleaf control; and d) demonstrate if crops grown in sequence with sugarbeet including field corn, dry bean (*Phaseolus vulgaris* L.), soybean and wheat can tolerate residues of ethofumesate at greater rates in sugarbeet.

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CHAPTER 2. SUGARBEET TOLERANCE TO POSTEMERGENCE ETHOFUMESATE 4SC

Introduction

Ethofumesate is a selective herbicide for preplant, preemergence, and postemergence control of monocotyledonous and dicotyledonous weeds at rates from 1.12 to 4.2 kg ai ha^{-1} in sugarbeet (Dexter 1975; Ekins and Cronin 1972; Eshel et al. 1976; Sullivan and Fagala 1970). Sugarbeet has excellent tolerance to ethofumesate applied preemergence at rates to 4.5 kg ha^{-1} in Minnesota and eastern North Dakota (Dexter 1976).

Schweizer (1975) reported sugarbeet tolerance was dependent on herbicide rate and soil type. For example, sugarbeet injury was greater on sandy loam soils compared with loam soils when ethofumesate was applied preplant at 4.5 kg ha^{-1} or more. However, sucrose content was not affected by herbicide application rate or soil type.

In Minnesota and eastern North Dakota, sugarbeet has excellent tolerance to ethofumesate applied to the soil at rates to 4.5 kg ha^{-1} (Dexter 1976). Excellent tolerance on prairie soils along with full-season residual soil activity (Elkins and Cronin 1972), especially on *Amaranthus* species (Schweizer 1975), makes ethofumesate a prime candidate for weed control in sugarbeet. Previous ethofumesate use rates allowed up to 0.38 kg ha^{-1} postemergence to sugarbeet greater than two-true leaves; however, the use rate of ethofumesate was increased to 4.48 kg ha^{-1} (Anonymous 2017).

Eshel et al. (1978) reported ethofumesate was absorbed primarily through emerging roots and shoots when soil-applied; however, ethofumesate uptake was limited when applied to sugarbeet hypocotyls. Ethofumesate rarely leaches in the soil profile due to low water solubility and high soil adsorption characteristics (Shaner 2014; Schweitzer 1975). Therefore, soil-applied ethofumesate usually remains in the hypocotyl zone of the sugarbeet in the soil with very little leaching to the root zone (Eshel et al. 1978) which could explain sugarbeet tolerance to decreased use rates.

There is minimal literature on sugarbeet tolerance to ethofumesate at rates greater than 0.38 kg ha^{-1} applied postemergence. Research evaluating ethofumesate rates greater than 0.38 kg ha^{-1} would have been off label before 2017; however, Generic Crop Science (Generic Crop Science LLC., Henderson, NV), in collaboration with the Beet Sugar Development Foundation (BSDF, Denver, CO), has developed a new label to increase ethofumesate POST use rates from 0.38 to 4.48 kg ha^{-1} to sugarbeet greater than two-true leaves (Anonymous 2017).

Implementing the updated label could provide sugarbeet growers with extended residual soil activity throughout the growing season, an additional tank mix option for a second site of action postemergence, and increased weed control from greater application rates. The benefits must be measured along with potential drawbacks of additional ethofumesate added to both foliage and soil which could create greater concentrations of herbicide near the root zone when leached, antagonistic tank mixtures, and increased injury to subsequent crops.

Experiments were conducted in the field and greenhouse to determine 1) sugarbeet tolerance to POST ethofumesate at rates up to 4.48 kg ha^{-1}, 2) sugarbeet tolerance to ethofumesate applications in different environments, including soil type and precipitation, and 3) sugarbeet tolerance to ethofumesate applied alone or in tank mixtures.

Material and Methods

Field Experiments

Field experiments were conducted at six locations relevant to sugarbeet production in Minnesota and eastern North Dakota in 2018 and 2019. Each site-year combination was considered an environment, totaling eight unique environments evaluated. Experiments were conducted near Downer, MN (46°52’09.3” N 96°31’08.6” W), Hickson, ND (46°42’21.4” N 96°48’03.5” W), Horace, ND (46°38’13.3” N 96°49’26.2” W), Prosper, ND (47°00’10.2” N 97°06’24.4” W) in 2018 and near Crookston, MN (47°48’44.2” N 96°36’51.1” W), Hickson, ND (46°42’21.4” N 96°48’03.5” W), Prosper, ND (47°00’12.3” N 97°06’54.4” W), and Wolverton, MN (46°35’10.7” N 96°42’33.7” W) in 2019. Field location descriptions are below (Table 2.1).

Table 2.1. Soil descriptions for sugarbeet tolerance experiments, 2018-2019.

Location	Year	Soil series and texture	Soil subgroup	Organic matter	Soil pH
				%	
Crookston	2019	Wheatville loam	Aeric calciaquolls	2.6	8.5
Downer	2018	Wyndmere fine sandy loam	Aeric calciaquolls	2.6	8.2
Hickson	2018	Fargo silty clay	Typic epiaquerts	7.1	7.5
Hickson	2019	Fargo silty clay	Typic epiaquerts	6.4	7.6
Horace	2018	Fargo silty clay	Typic epiaquerts	4.1	7.9
Prosper	2018	Bearden & lindaas silty clay loam	Aeric calciaquolls & Typic argiaquolls	3.8	8.1
Prosper	2019	Bearden & lindaas silt loam	Aeric calciaquolls & Typic argiaquolls	3.6	7.7
Wolverton	2019	Fargo silty clay	Typic epiaquerts	6.1	8.0

Field experiments were a randomized complete-block design with four or six replications, depending on environment. The experimental area was prepared for planting by fertilizing the area to a soil nitrogen level to 146 kg ha^{-1} according to the soil sample. Field cultivation was used to incorporate fertilizer and prepare the seed bed. Planting dates across years and sites ranged from May 3 to June 7 (Table 2.2) due to wet springs in 2018 and 2019.

Table 2.2. Field experiment plant and harvest dates, 2018-2019.

Location	Year	Planting date	Harvest date
Crookston	2019	May 13	September 17
Downer	2018	May 3	September 17
Hickson	2018	May 7	September 11
Hickson	2019	May 14	September 23
Horace	2018	June 7	October 2
Prosper	2018	May 14	September 18
Prosper	2019	May 16	October 30
Wolverton	2019	May 10	September 19

Rainfall data were collected from nearby weather stations operated by the North Dakota Agricultural Weather Network (NDAWN; https://ndawn.ndsu.nodak.edu/) and ClimateCorp FieldView (The Climate Corporation; https://climate.com/) in 2018 and 2019 growing seasons, respectively (Table 2.3).

Table 2.3. Rainfall throughout growing season across locations, 2018 and 2019.

	2018					
Month	Crookston	Downer	Hickson	Horace	Prosper	Wolverton
	---------------------------------------mm---------------------------------------					
March	-	-	-	-	-	-
April	21	4	4	4	4	4
May	44	14	14	14	54	14
June	130	148	148	148	79	148
July	73	117	117	117	65	117
August	34	92	92	92	78	92
Total Rainfall:	302	375	375	375	280	375
	2019					
March	21	-	21	19	30	22
April	41	15	33	31	38	31
May	42	56	90	90	68	85
June	51	81	56	72	101	68
July	100	136	169	157	152	99
August	97	70	60	72	106	61
Total rainfall:	351	358	429	442	495	366
Hist. normal[a]	381	409	409	409	398	387

[a]Historical monthly normal precipitation is North Dakota Agricultural Weather Network (NDAWN) at Eldred, MN; Sabin, MN; Prosper, ND; and Leonard, ND.

Each experimental unit was 3.3-m wide by 9-m long and included six rows planted 3-cm deep to a density of 152,000 (± 1,000) seeds ha^{-1} or approximately 12-cm spacing between seeds along rows spread 56-cm apart. Betaseed ‘7540’, (Betaseed, Inc., Shakopee, MN), a glyphosate-resistant sugarbeet seed treated with fluxapyroxad (Systiva XS, BASF Corporation, Research Triangle Park, NC), thiram (Thiram 42 S, Bayer Crop Science, Research Triangle Park, NC), and metalaxyl (Allegiance FL, Bayer Crop Science, Research Triangle Park, NC) fungicide at 17.44, 6, and 0.54 g active ingredient (ai), respectively, per kilogram, was planted. Seeds were also treated with insecticide clothianidin and beta-cyfluthrin (Poncho Beta, Bayer Crop Science, Research Triangle Park, NC) at 150 ml of product per 100,000 seeds. These pesticides reduce effects of insects and pathogens since the main focus of the experiment was to evaluate herbicide safety.

Fungicides controlling cercospora (*Cercospora beticola* Sacc.) and rhizoctonia (*Rhizoctonia solani* Kühn) were applied, as needed, throughout the growing season to reduce negative effects of foliar disease and confidently evaluate sugarbeet safety to herbicides. Weed control was maintained throughout safety trials to isolate crop safety treatment differences versus growth reduction from weed competition. Ethofumesate was broadcast to soil at 1.96 kg ha^{-1} and glyphosate at 1.26 kg ha^{-1} (Roundup PowerMAX, Monsanto Company, St. Louis, MO) was broadcast applied postemergence to reduce weed competition.

Treatments (Table 2.4) were applied using a bicycle-wheel plot sprayer with a shielded boom to reduce particle drift at 159 L ha^{-1} spray solution through 8002 XR flat-fan nozzles (XR TeeJet® Flat Fan Spray Tips, TeeJet® Technologies, Glendale Heights, IL) and pressurized with CO_2 at 276 kPa to the center-four rows of the experimental unit at the two-true leaf sugarbeet stage.

Table 2.4. Herbicide rates, and application timing for field experiments.[a]

Herbicide[b]	Rate	Timing[c]
	--kg ha^{-1}--	---leaves---
Ethofumesate	0	2-4
Ethofumesate	0.28	2-4
Ethofumesate	0.56	2-4
Ethofumesate	1.12	2-4
Ethofumesate	2.24	2-4
Ethofumesate	4.48	2-4

[a]High surfactant methylated oil concentrate at 1.8 L ha^{-1} added to each post treatment.
[b]Ethofumesate 4SC marketed by Generic Crop Science.
[c]Sugarbeet growth stage.

Sugarbeet tolerance to Ethofumesate 4SC was evaluated by counting sugarbeet plants in the middle-two rows of the experimental unit at the 2- to 4-leaf sugarbeet growth stage and again before harvest. Visible stature reduction was observed 7, 14, and 28 (±3) days after treatment (DAT) after the POST herbicide application on a scale of 0% to 100%, with a zero reflecting no reduction in above ground stature and a 100% reflecting complete loss in above ground stature compared to the untreated control rows between individual plots.

At harvest, sugarbeet were defoliated and harvested mechanically from the center two or three rows of each plot and weighed. A 10-kg sample was collected from each plot and analyzed at American Crystal Sugar Quality Lab, in East Grand Forks, MN, for sucrose content and sugar loss to molasses (SLM). Root yield (kg ha^{-1}), purity (%), and recoverable sucrose (kg ha^{-1}) were calculated. Sugarbeet root yield (kg ha^{-1}), percent sugar, and recoverable sucrose (kg ha^{-1}) were calculated and recorded based on lab results. Root yield, purity, and recoverable sucrose were calculated using the following calculations, respectively.

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

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

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

Data from the field experiment were analyzed using the MIXED procedure (method=type3) in SAS v. 9.4, SAS Institute, Cary, NC. Environment and replicate were considered random effects while treatments were fixed effects. If *F*-test was significant at $P \leq 0.05$, mean separation was performed using least squares means paired differences. Standard error was used to calculate *F*-protected least significant differences (LSD) at a significance level of P=0.05.

Greenhouse Experiments

Greenhouse experiments were conducted three times on sugarbeet planted into two soils in 2018. Each individual experiment was considered a 'run' with three replications. The soil types in the experiments were a Glyndon sandy-loam soil classified as coarse-silty, mixed, superactive, frigid Aeric Calciaquoll (Natural Resources Conservation Service 2018) from Ada, MN and Bearden silt-loam soil classified as fine-silty, mixed, superactive, frigid Aeric Calciaquoll (Natural Resources Conservation Service 2018) from Prosper, ND. Additional soil information is in Table 2.5.

Table 2.5. Soil descriptions for sugarbeet tolerance to ethofumesate, greenhouse, 2018.

Location	Soil series & texture	Soil subgroup	Organic matter	Soil pH
Ada, MN	Glyndon sandy loam	Aeric calciaquoll	2.2%	8.1
Prosper, ND	Beardon silt loam	Aeric calciaquoll	3.9%	8.0

A single sugarbeet variety, Crystal '981RR' (ACH Seeds, Inc., Eden Prairie, MN) was used throughout the experiment. The experiment was a randomized complete block design with a 6 x 2 factorial treatment arrangement. Treatments included six herbicide rates and two soil types. Plants were grown at 24 to 27C under natural light supplemented with a 16 h photoperiod providing 400 uE $m^{-2}s^{-1}$ light intensity.

Pots containing the sandy loam and silt loam soils were filled with 550 and 450 g of soil, respectively, and five sugarbeet seeds were equally spaced and planted to a depth of 2.5-cm in each pot. Pots were placed in the greenhouse and watered until the 2-leaf sugarbeet growth stage. Herbicide treatments (Table 2.6) were applied using a spray booth (Generation III, DeVries Manufacturing, Hollandale, MN) equipped with a TeeJet® 8001 XR nozzle calibrated to deliver 100 L ha^{-1} spray solution at 275 kPa and 4.8 km h^{-1}.

Table 2.6. Herbicide rates and application timing across experiments, greenhouse, 2018.

Herbicide[a]	Rate	Timing[b]
	--kg ha^{-1}--	---leaves---
Ethofumesate	0	2-4
Ethofumesate[c]	0.28	2-4
Ethofumesate	0.56	2-4
Ethofumesate	1.12	2-4
Ethofumesate	2.24	2-4
Ethofumesate	4.48	2-4

[a]Ethofumesate 4SC produced by Generic Crop Science
[b]Sugarbeet growth stage
[c]High surfactant methylated oil concentrate at 1.8 L ha^{-1} added to each post treatment.

Visible stature reduction (0% to 100%, 100% reflecting complete loss of stand) was evaluated 7 and 14 (±3) DAT. Sugarbeet shoot fresh weight and plant density were collected at the conclusion of every experiment.

Data from the greenhouse experiment were analyzed using the MIXED procedure (method=type3) in SAS v. 9.4, SAS Institute, Cary, NC. Each experiment run was considered a fixed effect. Soil type and herbicide rate factors were considered fixed effects while replicate was considered a random effect. If *F*-test was significant at $P \leq 0.05$, mean separation was performed using least squares means paired differences. The standard error and corresponding error degrees of freedom was used to calculate LSD at a significance level of P=0.05.

Results and Discussion

Sugarbeet Field Tolerance

Sugarbeet injury, noted as stature reduction, ranged from 0% to 29%, 7 to 28 DAT and was dependent on herbicide treatment and evaluation timing (Table 2.7). Stature reduction was a visible estimate of sugarbeet biomass in the herbicide treated plots as compared with the untreated rows between plots. We did not observe sugarbeet density reduction 7, 14, or 28 DAT (data not presented) nor at sugarbeet harvest.

Ethofumesate POST at 1.12 to 4.48 kg ha^{-1} reduced sugarbeet stature as compared with the untreated control or ethofumesate POST at 0.28 to 0.56 kg ha^{-1} at 7 and 14 DAT. However, sugarbeet recovered from stature reduction injury 28 DAT. Stature reduction from ethofumesate at 1.12 kg ha^{-1} was similar to stature reduction in the untreated control and 0.28 and 0.56 kg ha^{-1} ethofumesate at 28 DAT. Stature reduction from 2.24 and 4.48 kg ha^{-1} ethofumesate was greater than the untreated control at each evaluation.

Table 2.7. Stature reduction in response to Ethofumesate 4SC[a] rate, across environments, 2018-2019.[b]

	Stature reduction		
Ethofumesate[c]	7 DAT[d]	14 DAT	28 DAT
--kg ha^{-1}--	------------------------%------------------------		
Untreated control	0 a	0 a	0 a
0.28	2 a	1 a	0 a
0.56	2 a	2 a	1 a
1.12	7 b	6 b	2 a
2.24	16 c	14 c	8 b
4.48	28 d	29 d	18 c
LSD (0.05)	5	5	4
	------------------------P-value----------------------		
	<0.0001	<0.0001	<0.0001

[a]Ethofumesate 4SC marketed by Generic Crop Science.
[b]Means within a main effect not sharing any letter are significantly different by the LSD at the 5% level of significance.
[c]High surfactant methylated oil concentrate at 1.8 L ha^{-1} added to each post treatment.
[d]Stature reduction 7, 14, and 28 days after treatment (DAT).

Sugarbeet density (P=0.4305), root yield (P=0.1703), and sucrose content (P=0.2844) were not affected by ethofumesate (Table 2.8). Ethofumesate at 4.48 kg ha^{-1} reduced recoverable sucrose content (P=0.0410) to 8,990 kg ha^{-1} compared with 9,510 kg ha^{-1} for the untreated control. Although ethofumesate at 2.24 kg ha^{-1} reduced sugarbeet stature, recoverable sucrose was 9,130 kg ha^{-1} and was not different than the untreated control. Root yield and sucrose content averaged 67,200 kg ha^{-1} and 15.6% across all treatments and environments.

Table 2.8. Sugarbeet density, root yield, sucrose content, and recoverable sucrose in response to ethofumesate rate, across environments, 2018-2019.[a]

Ethofumesate[b]	Density	Root yield	Sucrose content	Recoverable sucrose
--kg ha^{-1}--	--30 m--	--kg ha^{-1}--	--%--	--kg ha^{-1}--
Untreated control	150	68,200	15.7	9,510 ab
0.28	149	67,500	15.6	9,350 abc
0.56	151	67,700	15.7	9,460 ab
1.12	150	68,600	15.7	9,540 a
2.24	153	65,200	15.7	9,130 bc
4.48	147	65,900	15.4	8,990 c
LSD (0.05)	NS	NS	NS	391
	------------------------------------P-value-----------------------------			
	0.4305	0.1703	0.2844	0.0410

[a]Means within a main effect column not sharing any letter are significantly different by the LSD at the 5% level of significance.
[b]High surfactant methylated oil concentrate at 1.8 L ha^{-1} added to each post treatment.

The experiment in Downer, MN in 2018 was not incorporated into the results. A variety of environmental factors caused too much variability within the experiment to accurately assess treatment differences. Sugarbeet yield components were not collected from Prosper, ND in 2019 due to excessive soil moisture conditions in September and October.

Stature reduction was observed from ethofumesate POST at 1.12 to 4.48 kg ha^{-1} at 7 and 14 DAT and from ethofumesate POST at 2.24 to 4.48 kg ha^{-1} at 28 DAT. We observed sugarbeet stature reduction as the ethofumesate POST rate increased, but ethofumesate did not reduce root yield at any rate in the field experiments. Several observations indicated ethofumesate 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). Likewise, Eshel et al. (1978) reported rapid ethofumesate movement upward from the base of the leaf to the tips of the leaf following postemergence application; however, the authors did not detect ethofumesate movement outside of the treated leaf to 15 days after application.

We believe ethofumesate reduced sugarbeet stature by damaging surface waxes (Abulnaja et al. 1992). Visible sugarbeet injury lessened throughout the growing season as new sugarbeet growth emerged, since ethofumesate does not translocate from the treated leaves (Eshel et al. 1978). We did not observe differences in sugarbeet row closure across treatments or decreased root yield or sucrose content.

Additionally, the compromised surface wax following the greater ethofumesate rates early in the growing season could have exposed sugarbeet to environmental or abiotic stresses, which may explain the reduction in recoverable sucrose at harvest.

Sugarbeet Greenhouse Tolerance

Sugarbeet stature reduction from ethofumesate ranged from 0% to 12% and 3% to 18% in the sandy loam and silt loam soil types, respectively, 7 DAT (Table 2.9). Sugarbeet recovered and stature reduction from ethofumesate was negligible at 14 DAT in both soil types. The average injury across ethofumesate rates were 5% and 14% and 3% and 9% stature reduction for sandy and silt loam soils, respectively, at 7 and 14 DAT.

Ethofumesate rate did not affect sugarbeet stature in either soil or at either evaluation timing. The results are consistent with field trial results where sugarbeet experienced stature reduction, especially from increased rates of ethofumesate early in the season; however, sugarbeet recovered, and sugarbeet injury was negligible later in the season.

Table 2.9. Sugarbeet fresh weight and stature reduction in response to ethofumesate rate and soil, greenhouse, 2018.[a]

	Sandy loam			Silt loam		
		Stature reduction			Stature reduction	
Ethofumesate[b]	Fresh weight	7 DAT[c]	14 DAT	Fresh weight	7 DAT	14 DAT
--kg ha^{-1}--	--g plant^{-1}--	-------%---------		--g plant^{-1}--	-------%------	
Untreated control	1.7	0	0	2.8	3	5
0.28	2.3	6	7	2.6	11	8
0.56	2.5	0	1	2.0	18	11
1.12	2.3	3	0	2.2	16	10
2.24	2.0	8	4	1.7	18	12
4.48	2.1	12	4	2.1	16	10
Average	2.2	5 b	3 b	2.2	14 a	9 a
LSD (0.05)						
Soil	NS	3	2	NS	3	2
Rate	NS	NS	NS	NS	NS	NS
Soil × rate	NS	NS	NS	NS	NS	NS
	---------------------------------------P-value-------------------------------					
Soil	0.8748	0.0053	0.0064	0.8748	0.0064	0.0966
Rate	0.9205	0.1351	0.1415	0.9205	0.1415	0.4428
Soil × rate	0.7209	0.0645	0.3632	0.7209	0.3632	0.3507

[a]Means within a main effect column not sharing any letter are significantly different by the LSD at the 5% level of significance.
[b]High surfactant methylated oil concentrate at 1.8 L ha^{-1} was added to each treatment.
[c]Stature reduction 7 and 14 days after treatment (DAT).

There was greater stature reduction in the silt loam soil compared with the sandy loam soil (Table 2.9). Schweizer (1975) reported sugarbeet root yield reduction following preplant-incorporated (PPI) applications of ethofumesate at 3.4, 4.5, and 9.0 kg ha^{-1} in a sandy loam soil; however, root yield reduction was only observed at the 9.0 kg ha^{-1} rate in a loam soil. There was greater soil crusting challenges with the silt loam as compared with the sandy loam, which may have contributed to increased stature reduction; however, increased sugarbeet injury was not observed on sandy loam soil when ethofumesate was applied POST, contrary to Schweizer (1975) results. Daily watering was implemented to overcome crusting issues from finely ground soil; however, this may have contributed to sugarbeet damping off.

Sugarbeet density was collected at the conclusion of the experiment to determine if ethofumesate POST, affected sugarbeet density; however, data was not presented due to excessive variability. Sugarbeet fresh weight tended to be unaffected by ethofumesate rate, however, fresh weight from sugarbeet treated with ethofumesate and grown in the silt loam soil tended to decrease as the ethofumesate rate increased compared with fresh weight from sugarbeet treated with ethofumesate and grown in a sandy loam soil. Ethofumesate POST at rates to 4.48 kg ha^{-1} did not reduce sugarbeet shoot fresh weight or stature across soil types and evaluation timings in the greenhouse; however, greater stature reduction was observed on silt loam soil compared with the sandy loam soil, which might also have been attributed to soil crusting.

Sugarbeet producers have applied up to 4.2 kg ha^{-1} ethofumesate preemergence and up to 0.38 kg ha^{-1} ethofumesate postemergence (Anonymous 2015) with excellent tolerance on prairie soils along with full-season residual soil activity (Elkins and Cronin 1972), especially on *Amaranthus* species (Schweizer 1975). Ethofumesate at rates up to 4.48 kg ha^{-1} postemergence must provide acceptable sugarbeet tolerance before sugarbeet producers will be willing to implement into a weed management system.

Field and greenhouse experiments demonstrate visible sugarbeet stature reduction from ethofumesate POST at rates from 1.12 kg ha^{-1} up to 4.48 kg ha^{-1}, 7 and 14 DAT (field); however, visible stature reduction decreased after 14 DAT (field and greenhouse). We did not observe any differences in row closure across treatments or environments in field experiments. These results were consistent with observations from other researchers (Bollman and Sprague 2007; Smith and Schweizer 1983). Smith and Schweizer (1983) reported sugarbeet overcame early season injury from PRE and POST herbicides and did not affect yield.

Our experiments conclude ethofumesate POST at rates to 1.12 kg ha^{-1} can be used for broadleaf weed control in sugarbeet production regions, based on these tolerance experiments.

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CHAPTER 3. ETHOFUMESATE 4SC POSTEMERGENCE EFFICACY ON COMMON LAMBSQUARTERS, REDROOT PIGWEED, AND WATERHEMP

Introduction

Weed control can be challenging in sugarbeet because of its slow growth early in the season, low competitive ability, and high sensitivity to pesticides (Jursik et al. 2008). Weeds compete for light, nutrients, and water, which causes crop failure if not controlled (Cioni and Maines 2011). Weed interference causes approximately a 70% loss in root yield in sugarbeet growing regions in North America (Soltani et al. 2018).

Extensive documentation of weed interference in sugarbeet production areas solidifies the importance of control throughout the growing season (Schweizer and Dexter 1987). Wicks and Wilson (1983) reported weed interference eight weeks after planting or four weeks after two-leaf stage affected sugarbeet yields. On average, a 70% to 30% ratio of broadleaf and grass weed species, respectively, are found in a sugarbeet field (Schweizer and May 1993). Annual broadleaf weeds are more competitive than annual grasses and often grow two to three times taller than sugarbeet by mid-summer.

Weeds that emerge early in the growing season are most difficult to control because of crop injury concerns due to low herbicide tolerance with sugarbeet seedlings (Schweizer and Dexter 1987). However, the optimal weed control timing is early in the season since smaller, newly emerged weeds are easier to control than larger, older weeds (Ritter 1989). Weed species mature as sugarbeet becomes larger, creating expanded root systems and above-ground plant parts that require much more herbicide for adequate weed control (Ritter 1989; Schweizer and Dexter 1987).

Common lambsquarters, redroot pigweed, and waterhemp are three troublesome weed species in the Red River Valley (Peters and Lystad 2017) because of challenging germination periods, herbicide resistance characteristics, and immense fecundity. Ethofumesate provides up to 10 weeks of residual control to grass and broadleaf weed species (Ekins and Cronin 1972). Reliable sugarbeet tolerance on prairie soils along with 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 and eastern North Dakota.

Herbicides are applied alone or in mixtures. Herbicide mixtures are frequently applied to many crops to improve weed control spectrum and to provide greater overall control compared with individual treatments (Eshel et al. 1976). Herbicides may be tank-mixed legally if all herbicides in mixtures are registered for use and if no prohibitions against mixtures appear on the label. For example, herbicide mixtures potentially may change physical and chemical properties resulting in antagonistic or synergistic interactions. These interactions can have positive or adverse effects on weed control and crop tolerance.

Herbicide mixtures are commonly used in sugarbeet. Eshel et al. (1976) reported ethofumesate at 2.0 kg ha^{-1} POST controlled 58%, 59%, and 52% redroot pigweed, wild mustard (*Sinapis arvensis* L.), and wild oat (*Avena fatua* L.), respectively. Ethofumesate mixtures with desmedipham improved weed control compared to either herbicide applied alone but also injured sugarbeet. The authors concluded mixtures of ethofumesate and desmedipham reduced sugarbeet stature more than the expected response which Colby’s test defined as synergism (Colby 1967).

Glyphosate is an important sugarbeet herbicide (Kniss et al. 2004). Glyphosate provides control of many grasses and broadleaf weeds; however, glyphosate does not have any residual weed control activity (Schweizer 1975). Applied alone, glyphosate fails to control species with resistant alleles (Baylis 2000) and may increase herbicide selection pressure following repeated applications (Racchi et al. 1997). However, ethofumesate applied with glyphosate potentially introduces a second herbicide for effective weed control, thereby reducing selection pressure and providing residual control which may improve control of later-emerging weeds.

The opportunity is to identify POST broadleaf herbicide options in sugarbeet that are efficacious against *Amaranthacea* and *Chenopodiaceae* species and provide residual weed control once it has been determined what sugarbeet growth stage herbicides will be most efficacious. Therefore, field and greenhouse experiments were conducted to 1) determine common lambsquarters, redroot pigweed, and waterhemp control with ethofumesate postemergence to 4.48 kg ha^{-1}; 2) determine if ethofumesate mixtures improve and increase the spectrum of weed control; and 3) determine application timings to maximize weed control alone or in mixtures.

Material and Methods

Field Experiments

Experiments were conducted at four sites in Minnesota and eastern North Dakota in 2018 and 2019. Experiments were conducted near Oslo, Moorhead, and Lake Lillian, MN and near Minto, ND. Each site-year combination was considered an environment, totaling six unique environments evaluated. Field location information is below (Table 3.1).

Table 3.1. Plant dates and weed species evaluated across environments.

Environment	Year	GPS coordinates	Plant date	Species evaluated
Lake Lillian, MN	2019	44°52'37.3"N - 94°58'45.7"W	May 7	Waterhemp; Common lambsquarters
Minto, ND	2019	48°20'15.9"N - 97°28'20.8"W	May 9	Redroot pigweed; Common lambsquarters
Moorhead, MN	2018	46°53'33.9"N - 96°45'21.2"W	May 15	Waterhemp; Common lambsquarters
Moorhead, MN	2019	46°53'30.6"N - 96°45'15.1"W	May 10	Redroot pigweed; Waterhemp; Common lambsquarters
Oslo, MN	2018	48°11’41.4N - 97°03’33.6”W	May 16	Redroot pigweed
Oslo, MN	2019	48°12'41.4"N - 96°56'40.9"W	May 11	Redroot pigweed; Common lambsquarters

Experiments were arranged as a randomized complete-block design with four replications. Each experimental unit was 3.3-m wide by 9-m long and included six rows of sugarbeet planted at a density of 152,000 (±1,000) pure live seeds ha^{-1}, or approximately at 12-cm spacing between seeds along rows spaced 56-cm apart. Field preparation, fertilization, and variety varied for each experiment; however, field operations were consistent with the common practices for sugarbeet production in the Red River Valley and south-central Minnesota.

Rainfall data were collected from nearby weather stations operated by the North Dakota Agricultural Weather Network (NDAWN) and ClimateCorp FieldView (Climate FieldView, The Climate Corporation) in 2018 and 2019 growing seasons, respectively (Table 3.2).

Table 3.2. Cumulative rainfall for environments.

Month	Lake Lillian	Minto	Moorhead	Oslo
	2018			
	---mm---			
March	33	-	-	-
April	35	2	6	2
May	69	61	44	61
June	70	78	123	78
July	199	62	81	62
August	76	13	101	13
Total Rainfall:	482	216	355	216
	2019			
March	46	16	30	22
April	108	40	50	31
May	141	41	92	51
June	111	54	98	67
July	122	86	145	126
August	85	98	91	75
Total Rainfall:	613	335	506	370
Hist. Normal[a]	432	361	374	361

[a]Historical monthly normal precipitation is North Dakota Agricultural Weather Network (NDAWN) at Campbell, MN (Lake Lillian, MN); Grafton, ND (Minto, ND); Fargo, ND (Moorhead, MN); and Warren, MN (Oslo, MN).

Postemergence treatments (Table 3.3) were applied to 5-cm weed species using a bicycle-wheel plot sprayer with a shielded boom to reduce particle drift at 159 L ha^{-1} spray solution through 8002XR flat fan nozzles (XR TeeJet® Flat Fan Spray Tips, TeeJet® Technologies, Glendale Heights, IL) spaced 51-cm apart and pressurized with CO_2 at 276 kPa to the center-four rows of the experimental unit at the two-true leaf sugarbeet stage.

Table 3.3. Herbicides, herbicide rate, and application timing for the efficacy experiments.

Treatment	Rate
	--kg ha^{-1}--
Glyphosate [a]	1.26
Phenmedipham	0.27
Acetochlor	0.94
Ethofumesate [b]	0.56
Ethofumesate [b]	1.12
Ethofumesate [b]	2.24
Ethofumesate [b]	4.48
Ethofumesate + glyphosate [c]	1.12 + 1.26
Ethofumesate + glyphosate [c]	2.24 + 1.26
Ethofumesate + phenmedipham [b]	1.12 + 0.27
Ethofumesate + phenmedipham [b]	2.24 + 0.27
Ethofumesate + acetochlor [c]	1.12 + 0.94
Ethofumesate + acetochlor [c]	2.24 + 0.94

[a]Ammonium sulfate at 2.5% v/v and non-ionic surfactant at 0.25% v/v were added to treatment.
[b]High surfactant methylated oil concentrate at 1.8 L ha^{-1} was added to treatment.
[c]Ammonium sulfate at 2.5% v/v and high surfactant methylated oil concentrate at 1.8 L ha^{-1} was added to treatment.

Evaluations included visible percent sugarbeet stature reduction (0% to 100%, 100% reflecting complete loss of stand) and visible percent weed control (0% to 100%, 100% reflecting complete weed control) 7 and 14 (±3) days after application. Estimates of surviving or new growth of weed density were measured using 0.25-m^2 quadrats by counting a weed species in four locations within a test plot 14 days (±3) days after application. Common lambsquarters plant height was collected at Moorhead, MN in 2018.

Data from the field experiments were analyzed using the MIXED procedure (method=type3) in SAS v. 9.4, SAS Institute, Cary, NC. Environment and replicate were considered random effects while treatment was fixed effects. If *F*-test was significant at $P \leq 0.05$, mean separation was performed using least squares means paired differences. Standard error was used to calculate *F*-protected LSD at a significance level of P=0.05.

Greenhouse Experiments

Common lambsquarters, redroot pigweed, and waterhemp were evaluated in separate experiments conducted in the greenhouse in 2018 and 2019. The greenhouse experimental design was a randomized complete block design with a factorial treatment arrangement and three replications. Treatment factors were herbicide treatment and plant height at herbicide application. Herbicide applications were applied PRE and to 1.3-, 2.5-, and 5-cm weed species. Experiments were repeated within each species. Plants were grown at 24 to 27C under natural light supplemented with a 16 h photoperiod that provided 400 uE $m^{-2}s^{-1}$ light intensity. Herbicide treatment list is in Table 3.4.

Table 3.4. Herbicide, herbicide rate, and weed height in greenhouse experiments.

Treatment	Rate
	---kg ha^{-1}---
Glyphosate[a]	1.10
Ethofumesate[b]	1.12
Glyphosate + ethofumesate[c]	1.10 + 1.12
Untreated control	0

[a]Ammonium sulfate at 2.5% v/v and non-ionic surfactant at 0.25% v/v were added to treatment.
[b]High surfactant methylated oil concentrate at 1.8 L ha^{-1} were added to treatment.
[c]Ammonium sulfate at 2.5% v/v and high surfactant methylated oil concentrate at 1.8 L ha^{-1} were added to treatment.

Plastic pots (10-cm by 10-cm) were filled approximately ¾-full with a peat, perlite, and vermiculite growth medium (Sunshine Mix No. 1, Downers Grove, IL) at pH 5.8 with 0.1 g weed seeds planted per pot. Plants were watered and fertilized as necessary. Treatments were applied when approximately 50 plants per pot reached desired treatment height. Plants were thinned to a similar density before herbicide application. Herbicide treatments were applied using a spray booth (Generation III, DeVries Manufacturing, Hollandale, MN) equipped with a single TeeJet® 8001XR nozzle (XR TeeJet® Flat Fan Spray Tips, TeeJet® Technologies, Glendale Heights, IL) calibrated to deliver 100 L ha^{-1} spray solution at 275 kPa and 4.8 km h^{-1}.

Visual weed control evaluations (0% to 100%, 100% reflecting complete weed control) were completed 7 and 14 (±3) days after treatment (DAT). Above-ground fresh weight (g pot^{-1}) and weed density were collected at the conclusion of the experiment or after the 14 DAT evaluation.

Data from the greenhouse experiments were analyzed using the MIXED procedure (method=type3) in SAS v. 9.4, SAS Institute, Cary, NC. The experiment was run twice for each weed species and each run was considered a fixed effect. Herbicide and weed height factors were considered fixed effects while replicate was considered random effect. If *F*-test was significant at $P \leq 0.05$, mean separation was performed using least squares means paired differences. The standard error and corresponding error degrees of freedom was used to calculate LSD at a significance level of P=0.05.

Results and Discussion

Sugarbeet Field Tolerance

Visible sugarbeet stature reduction was dependent on herbicide treatment across environments (Table 3.5). Acetochlor applied alone caused visual sugarbeet stature reduction similar to glyphosate alone. Glyphosate is applied on nearly 100% of sugarbeet fields in Minnesota and eastern North Dakota, an average of 2.2 times per acre (Peters et al. 2018) and has a well-established history of safe use across growth stages in sugarbeet (Peters 2017). Phenmedipham alone caused 21% stature reduction 7 DAT and 9% stature reduction at 14 DAT or sugarbeet injury greater than glyphosate alone.

Sugarbeet stature reduction from ethofumesate was dependent on rate. Stature reduction from 0.56 or 1.12 kg ha^{-1} ethofumesate POST was similar to glyphosate alone and was less than stature reduction from 2.24 or 4.48 kg ha^{-1} POST, 7 and 14 DAT.

Ethofumesate mixed with glyphosate increased sugarbeet stature compared with glyphosate alone; however, stature reduction was the same as ethofumesate alone at 1.12 or 2.24 kg ha^{-1}. Sugarbeet stature reduction from ethofumesate at 2.24 kg ha^{-1} mixed with glyphosate was greater than stature reduction from ethofumesate at 1.12 kg ha^{-1} with glyphosate. In general, stature reduction from ethofumesate plus (+) phenmedipham or ethofumesate + acetochlor was greater than stature reduction from ethofumesate + glyphosate, at either ethofumesate rate. Mixtures with ethofumesate significantly increased stature reduction across all herbicides.

Table 3.5. Sugarbeet visible stature reduction in response to herbicide application across environments.[a]

		Stature Reduction	
Treatment	Rate	7 DAT	14 DAT
	---kg ha^{-1}---	-------------%------------	
Glyphosate [b]	1.26	2 a	1 a
Phenmedipham[c]	0.27	21 cde	9 c
Acetochlor[c]	0.94	6 ab	5 abc
Ethofumesate [c]	0.56	3 a	3 ab
Ethofumesate [c]	1.12	8 ab	5 abc
Ethofumesate [c]	2.24	17 cd	18 d
Ethofumesate [c]	4.48	25 def	28 e
Ethofumesate + glyphosate [d]	1.12 + 1.26	14 bc	8 bc
Ethofumesate + glyphosate [d]	2.24 + 1.26	22 cdef	19 d
Ethofumesate + phenmedipham[c]	1.12 + 0.27	25 def	21 d
Ethofumesate + phenmedipham[c]	2.24 + 0.27	28 ef	28 e
Ethofumesate + acetochlor [d]	1.12 + 0.94	21 cde	21 d
Ethofumesate + acetochlor [d]	2.24 + 0.94	30 f	28 e
LSD (0.05)		8	5
		---------------P-value----------	
		<0.0001	<0.0001

[a]Means within a main effect not sharing any letter are significantly different by the LSD at the 5% level of significance.
[b]Ammonium sulfate at 2.5% v/v and non-ionic surfactant at 0.25% v/v were added to treatment.
[c]High surfactant methylated oil concentrate at 1.8 L ha^{-1} were added to treatment.
[d]Ammonium sulfate at 2.5% v/v and high surfactant methylated oil concentrate at 1.8 L ha^{-1} were added to treatment.

Duncan et al. (1981) reported reduced sugarbeet carbon dioxide (CO_2) uptake within 4 hours after ethofumesate POST at 2.2 kg ha^{-1} at the two- and six-leaf stage. Total photosynthesis was also reduced but recovered rapidly at the six-leaf sugarbeet stage; however, sugarbeet required 96 hours to evaluate significant recovery at the two-leaf sugarbeet stage.

Schweizer (1975) reported sugarbeet tolerance to ethofumesate PRE was attributed to application rate, which was also observed in ethofumesate POST applications throughout this study; however, Schweizer evaluated ethofumesate rates to 9.0 kg ha^{-1} applied to and incorporated into the soil. Although ethofumesate application was POST in our experiments, we believe sugarbeet injury was related to uptake via the root system following activation by rainfall.

The experiments conducted by Schweizer (1975) and Duncan et al. (1981) indicated sugarbeet stature reduction occurred; however, was followed by sugarbeet recovery. Their observations were similar to our observations in these efficacy experiments where stature reduction observed 7 DAT was either the same or less 14 DAT. Greater sugarbeet stature reduction from mixtures with ethofumesate could be due to added stress of not only metabolizing increased rates of ethofumesate, but also the addition of a second herbicide.

Overall, ethofumesate rates greater than 1.12 kg ha^{-1} either alone or mixed with glyphosate, phenmedipham, or acetochlor caused sugarbeet stature reduction; however, stature reduction tended to decrease from first to second evaluation. Experiments were terminated at 14 DAT since sugarbeet tolerance observations were confounded by effects from weed competition.

Common Lambsquarters Field Control

Common lambsquarters control ranged from 43% to 100% when herbicide treatments were evaluated 7 DAT and from 26% to 96% 14 DAT (Table 3.6). Glyphosate alone gave 98% and 95% control 7 and 14 DAT, respectively. While ethofumesate at 1.12 and 2.24 kg ha^{-1} + glyphosate provided 100% common lambsquarters control 7 DAT, applying ethofumesate with glyphosate did not significantly improve common lambsquarters control compared with glyphosate alone treatment.

Phenmedipham was sold commercially under the trade name ‘Betanal’ for broadleaf weed control including common lambsquarters, kochia, and wild mustard (Anonymous 2008) before the introduction of glyphosate. Common lambsquarters control from phenmedipham was statistically less than glyphosate at 7 DAT but there was no difference in common lambsquarters control between glyphosate and phenmedipham, 14 DAT.

Common lambsquarters control from acetochlor was 43% and 29%, 7 and 14 DAT, respectively. Common lambsquarters is one of the first weeds to germinate and emerge following sugarbeet planting (Curran et al. 2007; Giles and Cattanach, 2004; Smith 2003). In this study, common lambsquarters had already emerged at application time. These results demonstrate there is very little POST control from acetochlor alone and it is likely common lambsquarters emerged before acetochlor was made available to germinating seedlings by rainfall.

Armel et al. (2003) reported common lambsquarters control from acetochlor plus mesotrione [4- (methylsulfonyl)-2-nitrobenzoinc acid (MNBA)] was related to rainfall. They concluded acetochlor may not adequately control common lambsquarters under low rainfall conditions. We observed similar results in our field experiments, especially at our Minto, ND and Oslo, MN locations where limited rainfall occurred following herbicide application (Table 3.2).

Common lambsquarters control from ethofumesate generally increased as the ethofumesate rate increased. Common lambsquarters control from 1.12 kg ha^{-1} ethofumesate POST was greater than control from 0.56 kg ha^{-1} ethofumesate POST at 7 and 14 DAT. However, increasing the rate from 1.12 to 2.24 or 4.48 kg ha^{-1} did not consistently improve common lambsquarters control. Common lambsquarters control was greater for some of the treatments when ethofumesate was mixed with phenmedipham or acetochlor. Ethofumesate at 1.12 kg ha^{-1} + glyphosate, phenmedipham, or acetochlor gave similar common lambsquarters control compared with ethofumesate at 2.24 kg ha^{-1} + glyphosate, phenmedipham, or acetochlor.

Table 3.6. Common lambsquarters control in response to herbicide treatment 7 and 14 DAT across environments.[a]

		Common lambsquarters	
Treatment	Rate	7 DAT	14 DAT
	----kg ha^{-1}----	--------------%---------------	
Glyphosate	1.26	98 a	95 a
Phenmedipham	0.27	74 cd	81 abcd
Acetochlor	0.94	43 e	29 e
Ethofumesate	0.56	48 e	45 e
Ethofumesate	1.12	70 cd	66 d
Ethofumesate	2.24	64 d	77 bcd
Ethofumesate	4.48	79 bc	84 abc
Ethofumesate + glyphosate	1.12 + 1.26	100 a	96 a
Ethofumesate + glyphosate	2.24 + 1.26	100 a	95 a
Ethofumesate + phenmedipham	1.12 + 0.27	92 ab	89 ab
Ethofumesate + phenmedipham	2.24 + 0.27	95 a	94 a
Ethofumesate + acetochlor	1.12 + 0.94	75 cd	72 cd
Ethofumesate + acetochlor	2.24 + 0.94	77 cd	81 abcd
LSD (0.05)		13	16
		------------P-value-------------	
		<0.0001	<0.0001

[a]Means within a main effect not sharing any letter are significantly different by the LSD at the 5% level of significance.

Common lambsquarters height ranged from 9- to 58-cm and common lambsquarters average density ranged from 38 to 278 plants m^{-2} in 2018 (Table 3.7). Plant height was less from ethofumesate + glyphosate, ethofumesate + phenmedipham, and ethofumesate + acetochlor with ethofumesate at 2.24 kg ha^{-1} and from ethofumesate alone at 2.24 and 4.48 kg ha^{-1} compared with glyphosate, phenmedipham and acetochlor or ethofumesate at 0.56 and 1.12 kg ha^{-1} alone in 2018. However, herbicide treatments did not influence common lambsquarters density (P=0.7198) in 2018. Common lambsquarters density was influenced by herbicide treatment

(P=<0.0001) in 2019. This could be due to increased rainfall totals in the growing season of 2019 than in 2018 (Table 3.2). In 2019, common lambsquarters density was less from glyphosate alone or when 1.12 or 2.24 kg ha^{-1} ethofumesate was mixed with glyphosate or phenmedipham. Ethofumesate alone did not reduce common lambsquarters density in 2018 or 2019.

Table 3.7. Common lambsquarters height and density in response to herbicide treatment across two Moorhead, MN environments.[a]

		Height	Average density[b]		Density range[c]	
Treatment	Rate	2018	2018	2019	2018	2019
	---kg ha^{-1}---	---cm---	--------------------plant m^{-2}-------------------			
Glyphosate	1.26	19 d	160	66 a	40-288	21-174
Phenmedipham	0.27	33 f	278	321 b	64-536	220-408
Acetochlor	0.94	58 g	164	424 bc	56-312	236-720
Ethofumesate	0.56	24 e	148	323 b	32-304	184-424
Ethofumesate	1.12	17 cd	190	311 b	40-400	110-536
Ethofumesate	2.24	14 bc	136	314 b	40-272	197-476
Ethofumesate	4.48	9 a	106	380 b	8-256	280-536
Ethofumesate + glyphosate	1.12 + 1.26	11 ab	114	8 a	16-328	5-12
Ethofumesate + glyphosate	2.24 + 1.26	9 a	114	9 a	24-376	7-12
Ethofumesate + phenmedipham	1.12 + 0.27	12 ab	110	66 a	24-264	47-107
Ethofumesate + phenmedipham	2.24 + 0.27	10 a	38	51 a	24-48	25-66
Ethofumesate + acetochlor	1.12 + 0.94	19 d	96	334 b	8-304	296-400
Ethofumesate + acetochlor	2.24 + 0.94	11 ab	90	533 c	40-136	440-652
LSD (0.05)		3	NS	138		
		---------------P-value-------------				
		<0.0001	0.7198	<0.0001		

[a]Means within a main effect not sharing any letter are significantly different by the LSD at the 5% level of significance.
[b]Average common lambsquarters density per treatment.
[c]Range of common lambsquarters per treatment across replications.

Common lambsquarters density had greater spatial variability in 2018 compared with 2019, thus influencing herbicide treatment (Table 3.7). Density did not represent treatment differences but fit a spatial pattern within the field. We were unable to determine the cause for spatial variation; however, one contributing factor could be less rainfall in 2018 compared with 2019, creating a pattern within the field where common lambsquarters germination and emergence occurred as compared with a general flush of common lambsquarters we observed in 2019. Another factor could be variable weed height at application. Limited rainfall could have resulted in variable common lambsquarters emergence which would have created more variablilty when trying to target the set weed species height. The density ranges in 2019 reflected common lambsquarters populations consistent with treatment differences and visible evaluation percentages.

In summary, glyphosate plus ethofumesate provided the best overall common lambsquarters control; however, control was statistically comparable to glyphosate alone. Glyphosate alone reduced common lambsquarters height more than phenmedipham or acetochlor alone. Ethofumesate + phenmedipham at 1.12 + 0.27 kg ha^{-1} provided common lambsquarters control similar to ethofumesate + glyphosate at 1.12 + 1.26 kg ha^{-1} but reduced sugarbeet stature (Table 3.5). Common lambsquarters control tended to increase along with decreased common lambsquarters height as ethofumesate rate increased; however, ethofumesate alone did not reduce common lambsquarters density (Table 3.7).

Glyphosate provided acceptable common lambsquarters control in commercial sugarbeet fields in Minnesota and eastern North Dakota (Peters 2017). Increasing ethofumesate rate from 1.12 to 2.24 kg ha^{-1} did not improve control when mixed with either glyphosate or phenmedipham. These results indicate ethofumesate has limited POST efficacy and is not a stand-alone herbicide for common lambsquarters control postemergence.

Several observations conclude ethofumesate may affect surface waxes by reducing very long chain fatty acid and surface lipid formation (Abulnaja et al. 1992). The compromised surface wax of common lambsquarters could increase glyphosate penetration of the cuticle and improve overall control; however, the addition of ethofumesate to glyphosate applications did not result in increased common lambsquarters control in our field experiments.

Kniss and Odero (2013) reported ethofumesate and glyphosate mixture applied at the two-leaf sugarbeet stage reduced common lambsquarters density by 65%. They explained this could be either due to increased retention or absorption from ethofumesate, compromising the cuticle. They also reported increased ethofumesate rates led to increased weed control.

Kniss and Odero (2013) results were not compatible to what was observed in our study. They reported ethofumesate use in glyphosate resistant sugarbeet may increase the efficacy of glyphosate POST applications, especially on species such as common lambsquarters; however, our field study did not measure any significant increase in common lambsquarters control when adding ethofumesate to glyphosate. Kniss and Odero (2013) experiments were conducted using irrigation to supplement rainfall whereas our experiments relied on rainfall to activate herbicides. Limited rainfall at some of our field locations influenced our conclusions since ethofumesate must be rainfall incorporated to provide effective residual efficacy (Anonymous 2017).

Common Lambsquarters Greenhouse Control

Herbicide treatment interacted with weed height and affected common lambsquarters shoot fresh weight ($P = <0.0001$) but did not affect common lambsquarters visible control 7 DAT ($P = 0.2299$) and 14 DAT ($P = 0.5858$) or density ($P = 0.4440$) (Table 3.8). Herbicide treatments significantly affected common lambsquarters control, 7 and 14 DAT ($P = 0.0014$ and $P = 0.0001$) and common lambsquarters fresh weight ($P=0.0016$). Weed height at application significantly affected common lambsquarters control at 7 and 14 DAT ($P = 0.0014$ and $P = 0.0003$) and density ($P = 0.0106$).

Table 3.8. Sources of variation, degrees of freedom, and P-values for common lambsquarters visual control, shoot fresh weight, and density, greenhouse, 2019.

Source of variation	Df	Visual control 7 DAT	Visual control 14 DAT	Fresh weight	Density
		-------------------------P-value		-----------------------	
Herbicide	3	0.0014	0.0001	0.0016	0.0668
Height	3	0.0014	0.0003	<0.0001	0.0106
Herbicide × height	9	0.2299	0.5858	<0.0001	0.4440

The interaction between herbicide treatment and application timing on fresh weight was due to a linear regression of fresh weight and weed height in the untreated control (data not presented). The result of common lambsquarters plants with increased fresh weight as height increased in the untreated control would be expected. Since the other treatments did not respond in such a way, the interaction was significant due to the untreated control linear response compared with the other herbicide treatments.

Herbicide treatments controlled common lambsquarters, 7 and 14 DAT (Table 3.9). Common lambsquarters control ranged from 58% to 73% control 7 DAT and from 53% to 75% at 14 DAT. Common lambsquarters control with glyphosate or ethofumesate alone were similar to glyphosate + ethofumesate 7 DAT and greater than the untreated control.

Herbicide treatments continued to control common lambsquarters at 14 DAT. Common lambsquarters control with glyphosate + ethofumesate treatment was greater than glyphosate or ethofumesate alone. Improved control from glyphosate plus ethofumesate might be due to either increased glyphosate penetration through the compromised cuticle (Kniss and Odero 2013; Abulnaja et al. 1992) or residual control from ethofumesate (Duncan et al. 1981).

Table 3.9. Common lambsquarters control in response to herbicide treatment averaged across height at application timing, 7 and 14 DAT, greenhouse, 2019.[a]

Herbicide	7 DAT	14 DAT
	-----------------%--------------------	
Glyphosate	58 a	57 b
Ethofumesate	61 a	53 b
Glyphosate + ethofumesate	73 a	75 a
Untreated control	9 b	8 c
LSD (0.05)	18	13
	---------------P-value------------------	
Herbicide	0.0014	0.0001

[a]Means within a main effect not sharing any letter are significantly different by the LSD at the 5% level of significance.

Common lambsquarters plant height at application interacted with herbicide treatment and affected visible control 7 (P=0.0014) and 14 (0.0003) DAT and common lambsquarters density (P=0.0106) in pots (Table 3.10). Common lambsquarters control was greatest when glyphosate, ethofumesate, or glyphosate plus ethofumesate was applied PRE compared with POST, 7 and 14 DAT. Common lambsquarters density also interacted with weed height at herbicide application timing (Table 3.10). Density was less when herbicide treatments were PRE as compared with POST.

Table 3.10. Common lambsquarters control in response to height at application averaged across herbicide treatment, 7 and 14 DAT, greenhouse, 2019.[a]

	Visual control		
Weed height	7 DAT	14 DAT	Density
---cm---	-----------------%---------------		--plants / pot--
PRE	79 a	76 a	6 a
1.3	40 b	35 b	10 b
2.5	41 b	41 b	12 b
5	40 b	41 b	11 b
LSD (0.05)	11	10	3
	-------------------------P-value--------------------------		
Height	0.0014	0.0003	0.0106

[a]Means within a main effect not sharing any letter are significantly different by the LSD at the 5% level of significance.

Herbicide treatments applied PRE provided greater common lambsquarters control 7 and 14 DAT and reduced common lambsquarters density per pot compared with herbicide treatments applied POST to 1.3-, 2.5-, or 5-cm common lambsquarters. Ritter (1989) suggested new, small emerged weeds are easier to control compared with older, large weeds which supports these results.

Greenhouse results suggest adding ethofumesate as PRE to postemergence glyphosate applications can increase visible control and reduce common lambsquarters density compared to glyphosate alone. The combination of soil-applied herbicide and non-selective translocating herbicide could work together to suppress un-emerged weed species and kill susceptible emerged weed species. Kniss and Odero (2013) report that early application of ethofumesate to common lambsquarters species provided greater common lambsquarters control since the species emerges early in the growing season. This allowed longer residual control of un-emerged weed seeds.

The field experiment concluded no differences in common lambsquarters control between glyphosate and glyphosate plus ethofumesate. These results could be explained by timely rainfall in the greenhouse and untimely rainfall in the field setting. Ethofumesate must be incorporated to activate and provide residual efficacy (Anonymous 2017).

Overall, ethofumesate plus glyphosate applied PRE on common lambsquarters provided the greatest visible control and density reduction. However, timely rainfall must occur to realize the benefit of adding ethofumesate to glyphosate applications.

Redroot Pigweed Field Control

Redroot pigweed control ranged from 32% to 100% when evaluated 7 DAT and 15% to 98% when evaluated 14 DAT (Table 3.11). Ethofumesate alone at rates ranging from 0.56 to 4.48 kg ha^{-1} controlled 44% to 64% and 47% to 76% of redroot pigweed at 7 and 14 DAT, respectively. Redroot pigweed control was greater at 1.12 kg ha^{-1} ethofumesate alone compared with ethofumesate at 0.56 kg ha^{-1}, 14 DAT, but control did not increase as the ethofumesate rate increased from 1.12 to 4.48 kg ha^{-1}.

Glyphosate alone or glyphosate mixtures with ethofumesate at 1.12 or 2.24 kg ha^{-1} provided the best redroot pigweed control 7 or 14 DAT, however, ethofumesate did not improve redroot pigweed control when compared with the glyphosate alone at 7 DAT. Ethofumesate at 1.12 kg ha^{-1} alone or combined with glyphosate provided redroot pigweed control similar to ethofumesate at 2.24 kg ha^{-1} alone or combined with glyphosate, 14 DAT, suggesting the residual control benefit from ethofumesate.

Ethofumesate + phenmedipham or ethofumesate + acetochlor improved redroot pigweed control compared with phenmedipham or acetochlor alone. Redroot pigweed control from ethofumesate at 1.12 kg ha^{-1} plus either glyphosate, phenmedipham, or acetochlor was the same as redroot pigweed control from ethofumesate at 1.12 kg ha^{-1} alone.

Table 3.11. Redroot pigweed visible control in response to herbicide treatment at 7 and 14 DAT across environments.[a]

Treatment	Rate	7 DAT	14 DAT
	---kg ha^{-1}---	-------------%--------------	
Glyphosate	1.26	99 a	93 ab
Phenmedipham	0.27	32 h	15 f
Acetochlor	0.94	35 gh	43 e
Ethofumesate	0.56	44 fg	47 e
Ethofumesate	1.12	50 ef	62 d
Ethofumesate	2.24	54 def	71 cd
Ethofumesate	4.48	64 cd	76 cd
Ethofumesate + glyphosate	1.12 + 1.26	99 a	98 a
Ethofumesate + glyphosate	2.24 + 1.26	100 a	99 a
Ethofumesate + phenmedipham	1.12 + 0.27	74 bc	68 cd
Ethofumesate + phenmedipham	2.24 + 0.27	76 b	78 c
Ethofumesate + acetochlor	1.12 + 0.94	59 de	72 cd
Ethofumesate + acetochlor	2.24 + 0.94	70 bc	80 bc
LSD (0.05)		10	14
		-------------P-value-----------	
		<0.0001	<0.0001

[a]Means within a main effect not sharing any letter are significantly different by the LSD at the 5% level of significance.

Redroot pigweed density was affected by herbicide treatment at Oslo in 2018 and 2019 but was not affected by herbicide treatment at Minto in 2019 (Table 3.12). Glyphosate alone or glyphosate mixtures with ethofumesate at 1.12 and 2.24 kg ha^{-1} provided density reductions from 0 to 7 plants per m^{-2} or 99% to 100% control at Oslo in 2018 and 2019.

Table 3.12. Redroot pigweed density in response to herbicide treatment across three environments.[a]

Treatment	Rate	Average density[b] Oslo[d]	Average density[b] Minto-2019	Density range[c] Minto-2019
	---kg ha^{-1}---	---------------plants m^{-2}---------------		
Glyphosate	1.26	2 ab	5	0-13
Phenmedipham	0.27	31 c	253	101-562
Acetochlor	0.94	15 abc	309	23-836
Ethofumesate	0.56	22 c	166	87-336
Ethofumesate	1.12	14 abc	245	108-584
Ethofumesate	2.24	14 abc	309	78-896
Ethofumesate	4.48	21 c	263	22-560
Ethofumesate + glyphosate	1.12 + 1.26	0 a	4	0-15
Ethofumesate + glyphosate	2.24 + 1.26	0 a	7	0-20
Ethofumesate + phenmedipham	1.12 + 0.27	19 bc	264	10-780
Ethofumesate + phenmedipham	2.24 + 0.27	18 bc	163	1-552
Ethofumesate + acetochlor	1.12 + 0.94	17 abc	228	73-648
Ethofumesate + acetochlor	2.24 + 0.94	15 abc	259	15-704
LSD (0.05)		17	NS	
		--------P-value-------		
		0.0549	0.4512	

[a]Means within a main effect not sharing any letter are significantly different by the LSD at the 5% level of significance.
[b]Average common lambsquarters density per treatment.
[c]Range of common lambsquarters density per treatment across replications.
[d]Data reflects combined analysis of Oslo, MN in 2018 and 2019.

Increasing ethofumesate rate alone from 0.56 to 4.48 kg ha^{-1} did not reduce redroot pigweed density at Oslo in 2018 or 2019 or at Minto in 2019 (Table 3.12). This could be due to limited activating rainfall (Table 3.3). Decreased rainfall could create both sporadic weed emergence along with inactivation of herbicide applications, especially ethofumesate which requires a minimum of 15-mm of rainfall for activation (Anonymous 2017). Oslo received a total of 78 and 67 mm in 2018 and 2019, respectively, in June or the month the herbicide application was made. Likewise, Minto received 54-mm rainfall in 2019 in June. The lack of rainfall at Minto could explain the variability in redroot pigweed density observed throughout the field.

In summary, glyphosate alone or glyphosate mixtures with ethofumesate at 1.12 or 2.24 kg ha^{-1} provided the greatest visible redroot pigweed control (Table 3.11). Ethofumesate alone, regardless of rate, or ethofumesate mixed with glyphosate, phenmedipham, or acetochlor did not significantly improve redroot pigweed control compared with glyphosate alone.

Kniss and Odero (2013) reported significantly reduced redroot pigweed stand densities from ethofumesate mixtures with glyphosate at the two-true leaf sugarbeet stage. The results suggest early postemergence applications of glyphosate plus ethofumesate on small or un-emerged redroot pigweed can provide burndown and full season control, provided there is activating rainfall.

In our experiments, glyphosate alone provided excellent redroot pigweed control. Ethofumesate plus glyphosate also provided excellent control; however, increasing the ethofumesate rate above 1.12 kg ha^{-1} did not improve redroot pigweed control. Phenmedipham or acetochlor plus ethofumesate, at any rate, did not provide adequate control of redroot pigweed compared with the glyphosate treatments. Once again, the lack of activating rainfall following application could explain the reduced activity from ethofumesate alone or acetochlor plus ethofumesate mixtures.

Redroot Pigweed Greenhouse Control

Herbicide treatment interacted with herbicide application and affected redroot pigweed visible control, 7 and 14 DAT (P = 0.0054 and P = 0.0001) but did not affect redroot pigweed shoot fresh weight (P = 0.1416) or redroot pigweed density per pot (P = 0.3519) (Table 3.13).

Table 3.13. Sources of variation, degrees of freedom, and P-values for redroot pigweed visible control, fresh weight, and density, greenhouse, 2019.

		Visual control			
Source of variation	Df	7 DAT	14 DAT	Fresh weight	Density
		----------------------------P-value--------------------------			
Herbicide	3	<0.0001	<0.0001	<0.0001	0.0015
Height	3	0.1238	0.0368	0.2184	<0.0001
Herbicide × height	9	0.0054	0.0001	0.1416	0.3519

Herbicide treatment interacted with height at herbicide application and affected visual redroot pigweed control at 7 and 14 DAT (Figure 3.1 and 3.2). Application timing did not decrease the control provided by glyphosate alone or ethofumesate mixtures, 7 DAT. However, redroot pigweed control from ethofumesate alone decreased as redroot pigweed height at application increased from 1.3- to 5-cm at application. Glyphosate applied POST at 5-cm redroot pigweed provided similar control to glyphosate + ethofumesate mixtures at 7 and 14 DAT.

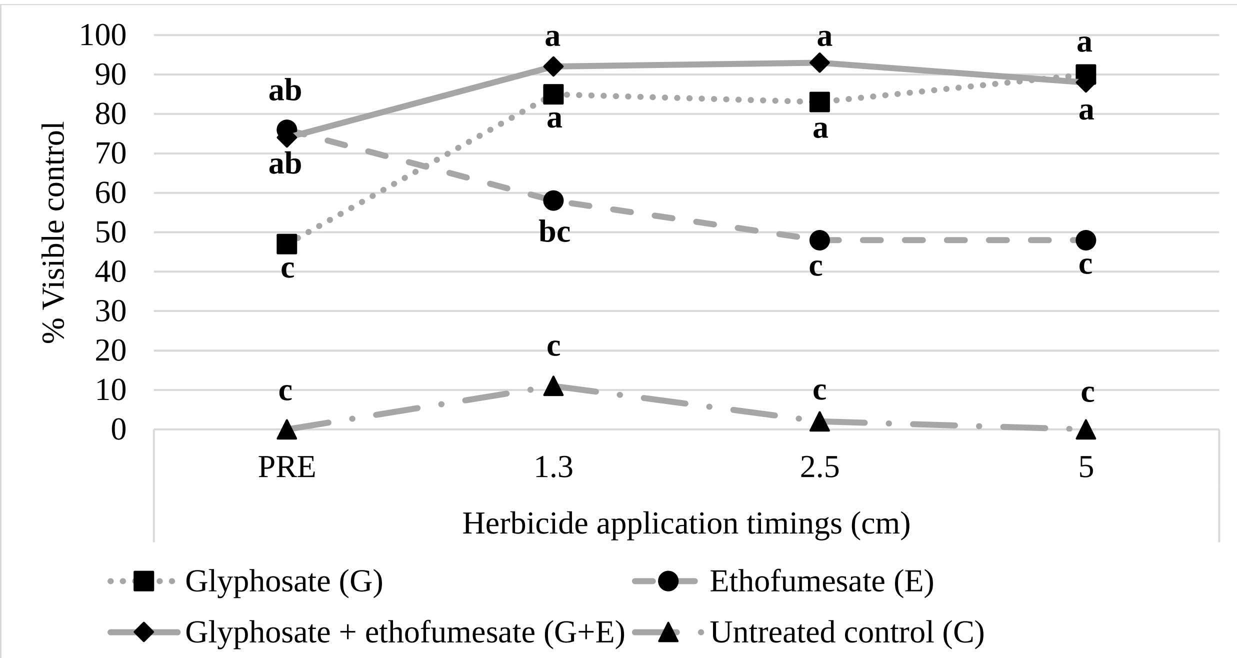

Figure 3.1. Redroot pigweed control 7 days after treatment (DAT) in response to herbicide treatment and application timing, greenhouse, 2019. Means within a main effect not sharing any letter are significantly different by the LSD at the 5% level of significance.

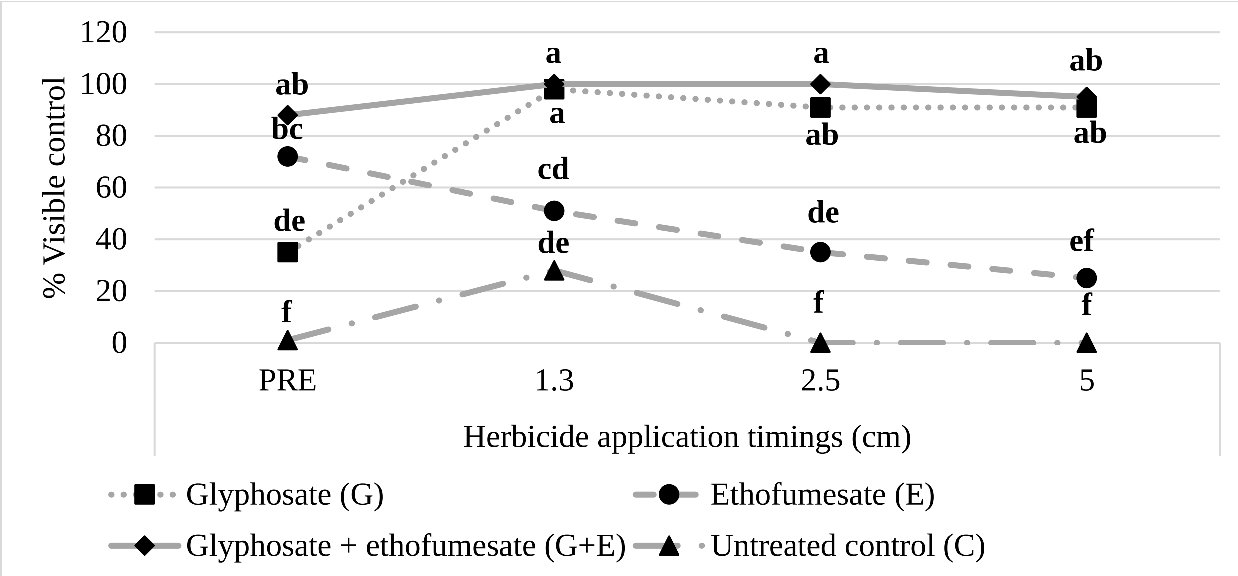

Figure 3.2. Redroot pigweed control 14 days after treatment (DAT) in response to herbicide treatment and application timing, greenhouse, 2019. Means within a main effect not sharing any letter are significantly different by the LSD at the 5% level of significance.

Herbicide treatment affected redroot pigweed shoot fresh weight (P=<0.0001) and plant density per pot (P=0.0015) (Table 3.14). Glyphosate alone or glyphosate + ethofumesate reduced redroot pigweed shoot fresh weight and density per pot compared to ethofumesate alone.

Table 3.14. Redroot pigweed fresh weight and density in response to herbicide treatment averaged across height at application timing, greenhouse, 2019.[a]

Treatment	Fresh weight	Density
	---g---	-plant / pot-
Glyphosate	0 a	3 a
Ethofumesate	0.3 ab	9 b
Glyphosate + ethofumesate	0 a	2 a
Untreated control	0.6 b	10 b
LSD (0.05)	0.3	3
	-----------------P-value------------------	
Herbicide	<0.0001	0.0015

[a]Means within a main effect not sharing any letter are significantly different by the LSD at the 5% level of significance.

Redroot pigweed density per pot was dependent on weed height (P=<0.0001) following glyphosate, ethofumesate and glyphosate + ethofumesate application (Table 3.15). Herbicides applied POST to 1.3- and 2.5-cm redroot pigweed reduced density per pot as compared with herbicides applied PRE.

Table 3.15. Redroot pigweed density in response to application timing averaged across herbicide treatment, greenhouse, 2019.[a]

Weed height	Density
---cm---	-plant / pot-
PRE	9 c
1.25	5 ab
2.54	4 a
5	6 b
LSD (0.05)	1
	---P-value---
Timing	<0.0001

[a]Means within a main effect not sharing any letter are significantly different by the LSD at the 5% level of significance.

In summary, glyphosate alone provided excellent redroot pigweed control in field experiments in 2018 and 2019. Results from greenhouse experiments were similar to results from field experiments and indicated glyphosate alone provides excellent redroot pigweed control. Ethofumesate residual benefits were demonstrated at the 14 DAT evaluation, but were mostly not significant as observed in the greenhouse study.

Kniss and Odero (2013) reported significantly reduced redroot pigweed densities after an application of ethofumesate with glyphosate mixture at the two-true leaf sugarbeet stage. The results suggest early postemergence applications of glyphosate plus ethofumesate on small or un-emerged redroot pigweed can provide late growing season control, however, these benefits were not observed in this study.

One explanation for not observing the same results as Kniss and Odero (2013) in the field experiments could be due to lack of rainfall. The redroot pigweed locations, Minto and Oslo, were either below the historical average in 2018 or received the greatest rainfall amounts well after applications were made (Table 3.3).

Timely rainfall is necessary to activate ethofumesate and realize residual benefits (Anonymous 2017); however, even in the greenhouse with timely rainfall, residual benefits were not noticed. In the greenhouse, activating rainfall was observed, however, the pre-measured seedbank within the pots could have ran out, making the comparison between residual activity and simply no more seed left to germinate, indistinguishable.

Our results suggest mixing ethofumesate with a postemergence herbicide such as glyphosate rather than applying alone POST. Our evaluations of mixing two soil-applied herbicides, such as ethofumesate plus acetochlor, as a POST treatment did not provide adequate redroot pigweed control (3.11). Although phenmedipham is a postemergence herbicide, we concluded it did not provide adequate broad spectrum weed control due to the efficacy observations on redroot pigweed (Table 3.11). Glyphosate alone or ethofumesate plus glyphosate provided the greatest redroot pigweed control across our experiments.

Waterhemp Field Control

Waterhemp control ranged from 46% to 91% and from 31% to 91%, 7 and 14 DAT, respectively (Table 3.16). Waterhemp control from glyphosate was 62% at 7 DAT and 53% at 14 DAT suggesting waterhemp was a population with a mix of susceptible and resistant alleles. Likewise, phenmedipham or acetochlor alone did not provide acceptable waterhemp control. Waterhemp control at 4.48 kg ha^{-1} ethofumesate was greater than control from 0.56 kg ha^{-1} ethofumesate at 7 and 14 DAT. There was no difference in waterhemp control between 1.12 or 2.24 kg ha^{-1} ethofumesate plus glyphosate, phenmedipham, or acetochlor at 7 and 14 DAT.

Table 3.16. Waterhemp visible control in response to herbicide treatment 7 and 14 DAT across environments.[a]

		Waterhemp	
Treatment	Rate	7 DAT	14 DAT
	---kg ha^{-1}---	--------------%---------------	
Glyphosate	1.26	62 bcd	53 cd
Phenmedipham	0.27	46 d	31 e
Acetochlor	0.94	54 d	49 d
Ethofumesate	0.56	58 cd	65 bcd
Ethofumesate	1.12	63 bcd	66 bc
Ethofumesate	2.24	74 abc	78 ab
Ethofumesate	4.48	80 ab	84 a
Ethofumesate + glyphosate	1.12 + 1.26	86 a	86 a
Ethofumesate + glyphosate	2.24 + 1.26	91 a	91 a
Ethofumesate + phenmedipham	1.12 + 0.27	76 abc	78 ab
Ethofumesate + phenmedipham	2.24 + 0.27	84 a	79 ab
Ethofumesate + acetochlor	1.12 + 0.94	77 ab	83 a
Ethofumesate + acetochlor	2.24 + 0.94	83 a	81 ab
LSD (0.05)		18	16
		-----------P-value------------	
		0.0001	<0.0001

[a]Means within a main effect not sharing any letter are significantly different by the LSD at the 5% level of significance.

Waterhemp density was affected by herbicide treatment at Moorhead in 2018 (P=0.0152) and at Lake Lillian in 2019 (P=0.0311) (Table 3.17). Glyphosate + ethofumesate at 2.24 kg ha^{-1} and ethofumesate alone at 4.48 kg ha^{-1} provided 0 plants per m^2 at Moorhead in 2018. Acetochlor alone and mixed with ethofumesate also provided good control with 3 to 8 plants per m^2 at Moorhead.

Glyphosate alone and glyphosate + ethofumesate at 1.12 or 2.24 kg ha^{-1} provided the greatest waterhemp density reduction with 1 plant per m^2 at Lake Lillian in 2019. Ethofumesate + phenmedipham or ethofumesate + acetochlor also reduced waterhemp density compared with ethofumesate, acetochlor, or phenmedipham alone.

Each location received activating rainfall (≥19 mm) within 3 to 5 days after the herbicide application which may explain the increased waterhemp density reduction across all treatments at these two locations. Werle et al. (2014) reported waterhemp germinated later (10% emergence at 230 growing degree days [GDD]) and for an extended period (766 GDDs accumulated between 10% and 90% emergence) than common ragweed (*Ambrosia artemisiifolia* L.) and kochia [Bassia scoparia (L.) A.J. Scott] (10% emergence at 19 GDD and 108 GDDs accumulated between 10% and 90% emergence), which are two additional important weeds in sugarbeet production areas in Minnesota an eastern North Dakota. Glyphosate and phenmedipham alone had the greatest plant density compared with all other treatments in Moorhead in 2018. The same result was not observed at the other location, potentially due to a decreased pressure of non-resistant waterhemp biotypes at Lake Lillian compared with Moorhead.

Table 3.17. Waterhemp density in response to herbicide applications across environments and years.[a]

		Density	
Treatment	Rate	Moorhead-2018	Lake Lillian-2019
	---kg ha^{-1}---	---------plants m^{-2}-------	
Glyphosate	1.26	24 c	1 a
Phenmedipham	0.27	24 c	9 b
Acetochlor	0.94	3 ab	9 b
Ethofumesate	0.56	16 abc	10 b
Ethofumesate	1.12	16 abc	9 b
Ethofumesate	2.24	2 ab	9 b
Ethofumesate	4.48	0 a	9 b
Ethofumesate + glyphosate	1.12 + 1.26	18 bc	1 a
Ethofumesate + glyphosate	2.24 + 1.26	0 a	1 a
Ethofumesate + phenmedipham	1.12 + 0.27	8 abc	5 ab
Ethofumesate + phenmedipham	2.24 + 0.27	8 abc	7 ab
Ethofumesate + acetochlor	1.12 + 0.94	6 ab	8 ab
Ethofumesate + acetochlor	2.24 + 0.94	4 ab	8 ab
LSD (0.05)		16	7
		-----------P-value-----------	
		0.0152	0.0311

[a]Means within a main effect not sharing any letter are significantly different by the LSD at the 5% level of significance.

Waterhemp germinates and emerges later than common lambsquarters and redroot pigweed (Hartzler et al. 1999; Werle et al. 2014). A survival benefit of weeds that have late emergence patterns is emergence after the last postemergence herbicide application in the presence of glyphosate-resistant biotypes has been made (Boerboom 2002). The addition of ethofumesate provides residual control (Ekins and Cronin 1972) after the first postemergence application which could explain the increased visual waterhemp control.

These data suggest waterhemp control can be achieved with an effective POST herbicide combined with ethofumesate for residual control, as compared with common lambsquarters or redroot pigweed results. The results suggest the best control of waterhemp would be glyphosate + ethofumesate at 1.12 or 2.24 kg ha^{-1}. Ethofumesate alone at 4.48 kg ha^{-1} provided similar waterhemp control, however, the input cost would be greater than ethofumesate plus glyphosate at 2.24 kg ha^{-1} and sugarbeet stature reduction would increase compared with lower rates of ethofumesate plus glyphosate.

Waterhemp Greenhouse Control

Herbicide treatment interacted with weed height at herbicide application timing and affected waterhemp visible control, 7 and 14 DAT (P = <0.0001 and P = 0.0007) and waterhemp density in pots (P = 0.0006) (Table 3.18). Herbicide treatment did not interact with timing or affect waterhemp shoot fresh weight (P = 0.1378).

Table 3.18. Sources of variation, degrees of freedom, and P-values for waterhemp visual control, fresh weight, and density, greenhouse, 2019.

		Visual control			
Source of variation	df	7 DAT	14 DAT	Fresh weight	Density
		-------------------------P-value-----------------------			
Herbicide	3	<0.0001	<0.0001	<0.0001	0.0003
Height	3	0.0665	0.0008	0.0025	0.0257
Herbicide × height	9	<0.0001	0.0007	0.1378	0.0006

Herbicide treatment affected waterhemp visible control, 7 and 14 DAT (Figure 3.4 and 3.5) and waterhemp density per pot (Figure 3.6). Glyphosate + ethofumesate or ethofumesate PRE provided 100% and 98% waterhemp control, respectively, at 7 DAT. Glyphosate controlled

1.3-cm waterhemp similar to ethofumesate, 7 DAT, however, control was less than glyphosate + ethofumesate. Glyphosate + ethofumesate controlled at 2.5-cm waterhemp was greater than glyphosate alone. Ethofumesate and glyphosate provided similar control of 2.5-cm waterhemp. Glyphosate + ethofumesate and ethofumesate alone provided similar control of 5-cm waterhemp and control was greater than waterhemp control from glyphosate alone.

Ethofumesate alone and glyphosate + ethofumesate PRE continued their excellent waterhemp control, 14 DAT. However, waterhemp control from glyphosate + ethofumesate or ethofumesate alone POST was less than waterhemp control PRE. Glyphosate + ethofumesate provided similar control compared with ethofumesate alone for control of 5-cm waterhemp.

Waterhemp density per pot was dependent on herbicide treatment and waterhemp height at application timing (Figure 3.6). Ethofumesate or glyphosate + ethofumesate provided complete waterhemp control PRE. There was no difference in density per pot of 1.3-cm waterhemp between glyphosate or ethofumesate alone; however, glyphosate + ethofumesate reduced plant density of 1.3-cm waterhemp. Waterhemp density was greater when herbicide treatments were applied to 2.5- or 5-cm waterhemp compared to herbicide treatments applied PRE and early POST.

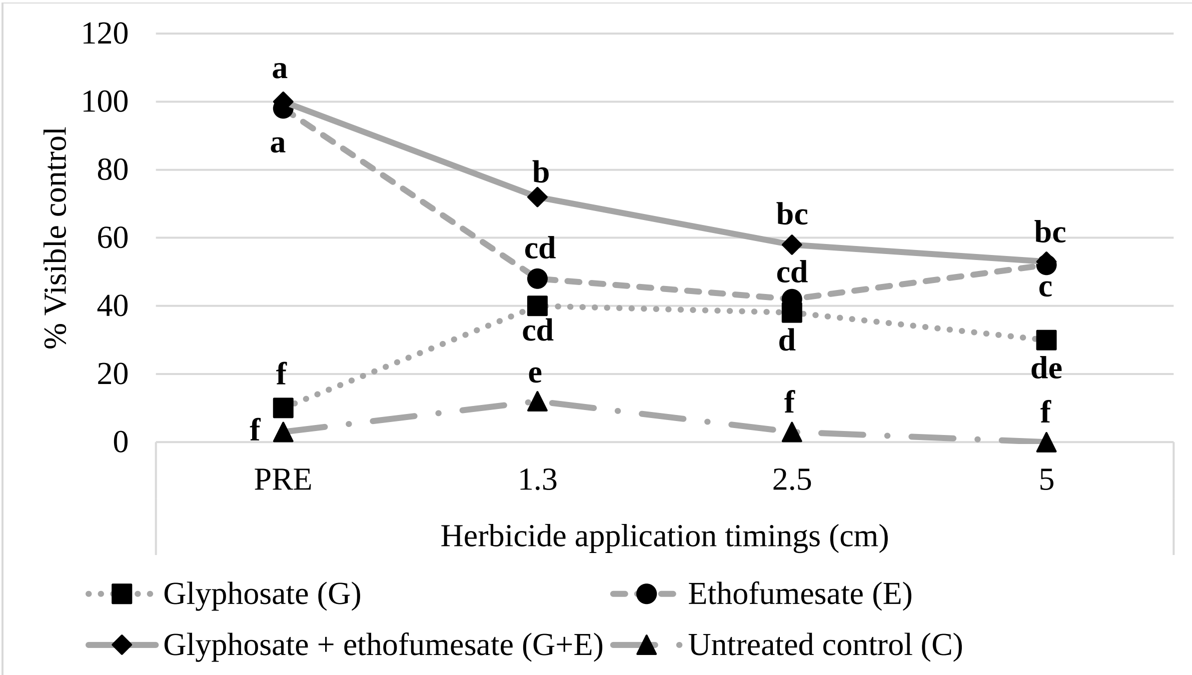

Figure 3.3. Waterhemp control 7 days after treatment (DAT) in response to herbicide treatment and application timing, greenhouse, 2019.

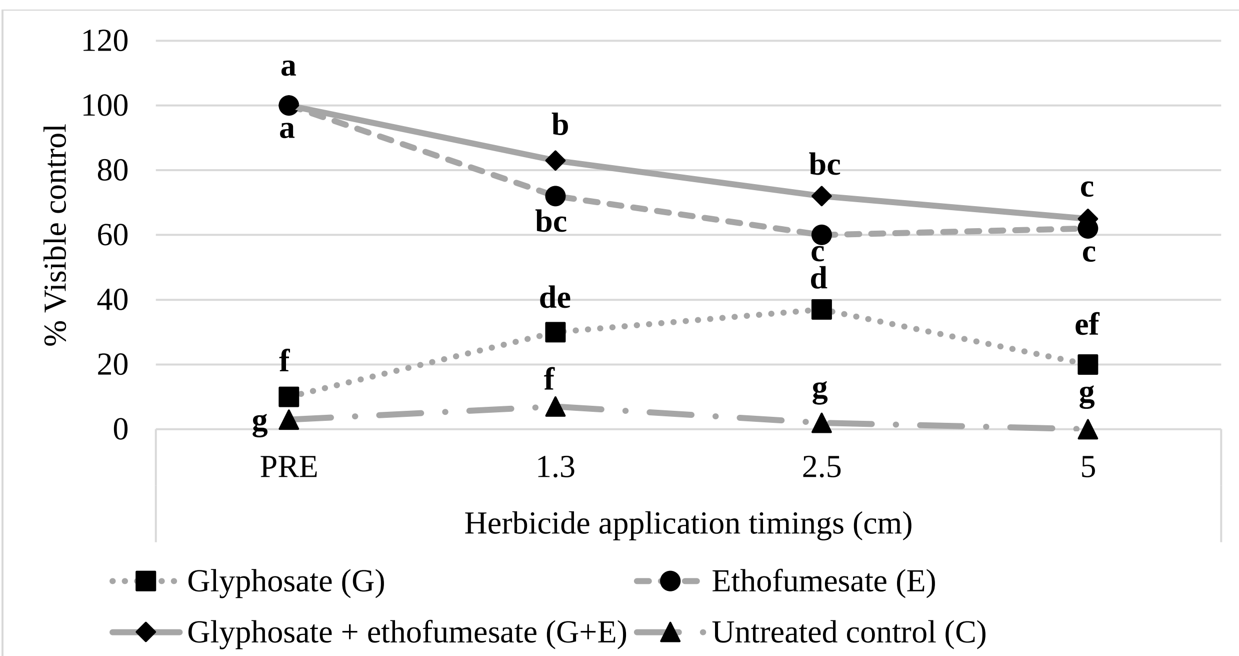

Figure 3.4. Waterhemp control 14 days after treatment (DAT) in response to herbicide treatment and application timing, greenhouse, 2019.

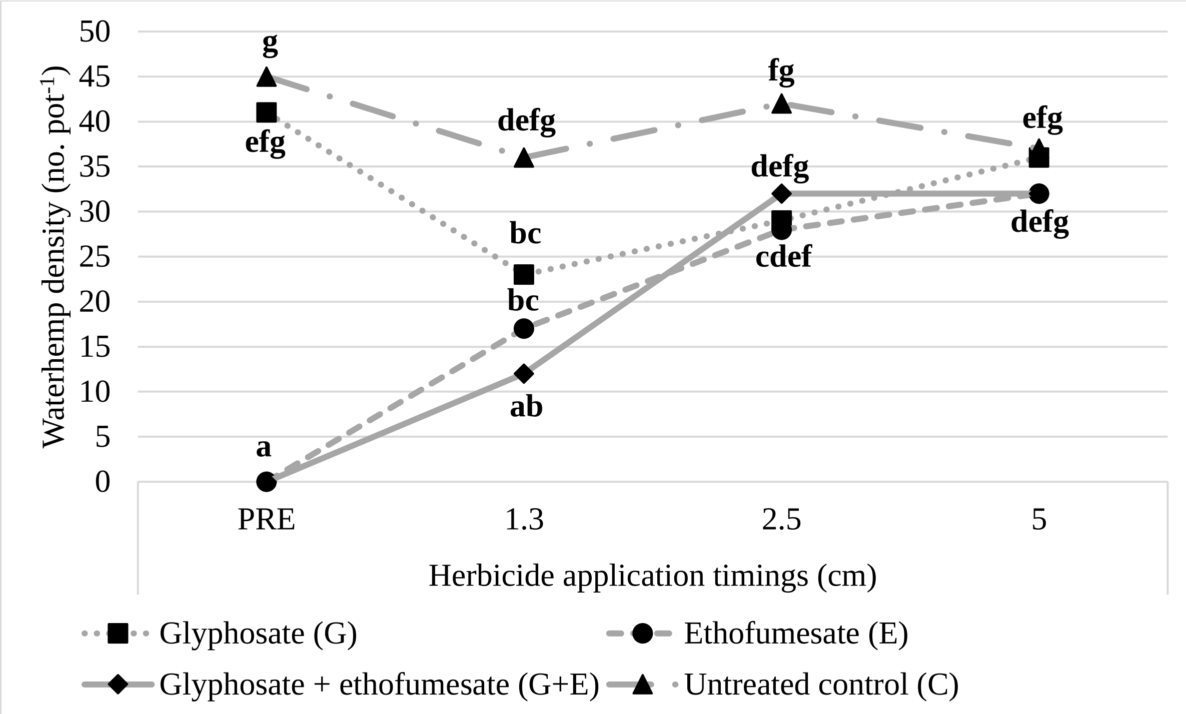

Figure 3.5. Waterhemp density in response to herbicide treatment and application timing, greenhouse, 2019.

Waterhemp shoot fresh weight was affected by herbicide treatment (Table 3.19). Glyphosate + ethofumesate or ethofumesate alone reduced waterhemp shoot fresh weight compared with glyphosate alone. Glyphosate alone reduced waterhemp fresh weight compared with the untreated control.

Table 3.19. Waterhemp fresh weight in response to herbicide treatment averaged across height at application timing, greenhouse, 2019.[a]

Herbicide	Fresh weight
	---g---
Glyphosate	0.46 b
Ethofumesate	0.18 a
Glyphosate + ethofumesate	0.14 a
Untreated check	0.88 c
LSD (0.05)	0.12
	---P-value---
Herbicide	<0.0001

[a]Means within a main effect not sharing any letter are significantly different by the LSD at the 5% level of significance.

Waterhemp shoot fresh weight was dependent on weed height (P=0.0025) following glyphosate, ethofumesate, or glyphosate + ethofumesate application (Table 3.20). Herbicides applied PRE and early POST reduced waterhemp shoot fresh weight as compared with herbicides applied over 2.5- or 5-cm waterhemp.

Table 3.20. Waterhemp fresh weight in response to application timing averaged across herbicide treatment, greenhouse, 2019.[a]

Weed height	Fresh weight
---cm---	----g----
PRE	0.22 a
1.3	0.30 a
2.5	0.56 b
5	0.58 b
LSD (0.05)	0.15
	--P-value--
Height	0.0025

[a]Means within a main effect not sharing any letter are significantly different by the LSD at the 5% level of significance.

The biology of waterhemp plays an important role when determining how to control this species. Additional factors contributing to difficult management include environmental plasticity, rapid and indeterminate growth, numerous seed production, and seed dormancy (Costea et al. 2005). Waterhemp has also been assumed to have similar physiological traits to other *Amaranthus* spp. such as increased photosynthetic rates in high temperatures and light intensity, reduced photorespiration, and greater water use efficiency.

Hartzler et al. (1999) reported increased emergence of waterhemp (*A. rudis*) and hairy cupgrass (*E. villosa*) due to increased rainfall and GDD accumulation throughout the months of May and June. The combination of biological waterhemp factors makes controlling this species difficult in weed management systems, especially when not using a residual herbicide or late season weed control.

Ethofumesate alone or mixed with glyphosate and applied early POST before waterhemp is 1.3-cm in height, provides a residual layer in the soil for this delayed emerging species. Glyphosate plus ethofumesate can control emerged waterhemp and provided residual control of later germinating waterhemp compared with ethofumesate alone. The greenhouse results supported the field experiment conclusion that waterhemp control can be achieved with an effective POST herbicide combined with ethofumesate for residual control.

A hypothesis from these experiments is POST applications of glyphosate for waterhemp control not only selects for individuals with herbicide resistant traits, but also, delayed emergence. As a result, susceptible species may germinate and emerge early in the season and will be controlled by glyphosate; however, waterhemp with resistant alleles will likely germinate later in the growing season and will not be controlled, resulting in weed escapes throughout the field. The addition of ethofumesate could act as a control "blanket" over the soil surface to inhibit germination of resistant waterhemp species.

Although ethofumesate alone provided similar waterhemp control as compared with glyphosate plus ethofumesate, applying ethofumesate alone at 4.48 kg ha^{-1} may not be an effective strategy due to less sugarbeet tolerance at higher rates and increased input costs from high rates of ethofumesate compared with lower rates of ethofumesate mixed with glyphosate. Glyphosate applied with ethofumesate also controls other broadleaf weeds in fields including redroot pigweed and common lambsquarters, in addition to potentially controlling early germinating waterhemp with susceptible alleles.

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CHAPTER 4. ETHOFUMESATE 4SC ROTATIONAL CROP TOLERANCE

Introduction

Monocotyledonous crops, including wheat and field corn are important rotational crops with sugarbeet in Minnesota and North Dakota (Tanner 1948; Jantzi et al. 2018). Ethofumesate residues 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-grain plantings with shallow tillage (Schroeder and Dexter 1979). Schroeder and Dexter (1979) reported wheat was more sensitive to ethofumesate residues than barley or soybean 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 and other sugarbeet producing geographies.

Schweizer (1977) reported barley and wheat stand density reduction and reduced vigor following broadcast ethofumesate application compared with band application on sugarbeet and when barley and wheat seedbed preparation followed superficial tillage on sugarbeet stubble compared with deep plowing. Finally, microbial activity, especially under warm and moist conditions, accounted for accelerated ethofumesate degradation compared with dry and cold soils (Schweizer 1976; van Hoogstraten et al. 1974).

The Ethofumesate 4SC label has expanded to include POST application alone and in mixtures from 0.38 to 4.48 kg ha^{-1} to sugarbeet with greater than two-true leaves and the pre-harvest interval (PHI) was reduced from 90 to 45 days (Anonymous 2017). 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 experiment was to a) evaluate sugarbeet tolerance from ethofumesate POST at rates up to 4.48 kg ha^{-1} and b) demonstrate crops grown in sequence with sugarbeet including corn, dry bean, soybean, and wheat can tolerate residues from ethofumesate POST at greater rates in sugarbeet than were previously used.

Material and Methods

Field experiments were conducted near Crookston, Foxhome, and Lake Lillian, MN, Prosper, ND, and Richville, MI in 2017 and 2018, totaling five environments evaluated. Each site-year combination was considered an environment. 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 approximately 3-cm deep after tillage to sugarbeet. 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 replicates. Experiment details at each location can be found in Table 4.1 and 4.2.

Table 4.1. Sugarbeet hybrid, seeding date, seeding rate and row spacing for field locations in 2017.

Location	GPS coordinates	Planting date	Sugarbeet hybrid	Seeding rate	Row spacing
				--S ha^{-1}[a]--	--cm--
Crookston	47°48’45.6” N -96°36’53.9” W	May 3, 2017	BT80RR52	149,435	56
Foxhome	46°21’43.6” N -96°23’01.7” W	May 12, 2017	HM4062	156,499	56
Lake Lillian	44°54’23.0” N -94°53’44.0’ W	May 6, 2017	BT9230	147,696	56
Prosper	47°00’08.5” N -97°06’24.3” W	May 2, 2017	SV36271RR	149,435	56
Richville	43°24’42.8” N -83°40’41.3” W	April 18, 2017	HM9619RR	125,353	76

[a]Seeds per hectare.

Table 4.2. Soil texture, organic matter, and pH across field locations in 2017.

Location	Soil texture	OM[a]	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

[a]Organic Matter.

Precipitation data were collected from nearby weather stations operated by the North Dakota Agricultural Weather Network (NDAWN; https://ndawn.ndsu.nodak.edu/), Community Collaborative Rain, Snow and Hail Network (CoCoRaHS; https://www.cocorahs.org/), the University of Minnesota Experiment Station, and the Michigan Automated Weather Network (MAWN; https://mawn.geo.msu.edu/) (Table 4.3).

Table 4.3. Annual precipitation in field experiments in 2017-2018 across locations.

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

[a]Historical average = 10-year average.
[b]9-year historical average.

Ethofumesate POST was timed to a calendar date in June, July, and August in 2017 to simulate 11-, 10-, and 9-month crop rotation intervals, respectively, in addition to a sequential application timed approximately every two weeks, for corn, dry bean, soybean, and wheat seeded in 2018. Ethofumesate rate, timing of application, and sugarbeet growth stage at application are listed in Table 4.4. Lake Lillian, MN did not receive the 10-month crop rotation interval treatment due to site constraints.

Table 4.4. Herbicide treatment, application rate, timing of application, and sugarbeet growth stage in 2017.

Treatment[a]	Rate	Timing of application	Sugarbeet growth stage
	--kg ha^{-1}--		# lvs
Untreated control	0		
Ethofumesate	1.12	Sequential[b]	2/10/14/18
Ethofumesate	4.48	June 15	10
Ethofumesate	4.48	July 15	18
Ethofumesate	4.48	August 15	22

[a]High-surfactant methylated oil concentrate (HSMOC) was used in all treatments across all locations.
[b]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 8002XR flat fan or 11002 Turbo TeeJet nozzles (TeeJet Technologies, Glendale Heights, IL) spaced 51-cm apart and pressurized with CO_2 at 345 kPa to all six rows of the six-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 (±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.

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

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

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

Experiments were prepared for corn, dry bean, soybean, and wheat seeding in spring 2018 with tillage 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 4.5 and dry bean and soybean in Table 4.6. Weeds, insects, and diseases were managed throughout the 2018 growing season.

Table 4.5. Corn and wheat seeding date, variety, and seeding rate for field locations in 2018.

Location	Wheat			Corn		
	Seeding date	Cultivar	Seeding rate	Seeding date	Hybrid	Seeding rate
			-kg ha^{-1}-			--S ha^{-1a}--
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[b]	N/A	N/A	May 1, 2018	Stine 9316	79,040

[a]Seeds per hectare.
[b]Wheat crop not evaluated in Richville, MI

Table 4.6. Dry bean and soybean seeding date, variety and seeding rate for field locations in 2018.

Location	Soybean			Dry Bean		
	Seeding date	Cultivar	Seeding rate	Seeding date	Cultivar	Seeding rate
			--S ha^{-1a}--			--S ha^{-1}--
Prosper	May 14, 2018	AG0934RR2	370,500	N/A[b]	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

[a]Seeds per hectare.
[b]Dry Bean crop only evaluated in Richville, MI.

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; and May 31, June 15, June 29, July 16, July 17, and August 14 at Richville, MI. Evaluations were a visual estimate of percent injury ranging from 0% (no injury) to 100% (all plants completely eliminated) relative to the untreated check rows between individual plots. 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 (cm) measured at the last evaluation was the average of 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) and corn, dry bean, soybean, and wheat grain yield were 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 v. 9.4, SAS Institute, Cary, NC. 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 squares means paired differences. Standard error was used to calculate *F*-protected least significant differences (LSD) at a significance level of P=0.05.

Results and Discussion

Sugarbeet Tolerance

Sugarbeet injury reported as chlorosis or stature reduction was negligible across ethofumesate treatment at any environment throughout the growing season in 2017 and 2018 (data not presented). Herbicide treatment did not affect root yield or recoverable sucrose in any environment (Table 4.7). Sucrose content was greater (P=0.0010) when 1.12 kg ha^{-1} of ethofumesate was applied at the 2-lf stage and repeated three times on approximately 14 day intervals (sequence) or when 4.48 kg ha^{-1} of ethofumesate was applied June 15 (11-month interval) compared with the untreated control or 4.48 kg ha^{-1} of ethofumesate applied August 15 (9-month interval) at Foxhome, MN. Harvest data from Prosper, ND or Richville, MI were not included in the analysis due to emergence issues and resultant site variability related to weather conditions at planting.

Table 4.7. Root yield, sucrose content, and recoverable sucrose for sugarbeet in response to timing of ethofumesate application, by environments in 2017.

	Crookston, MN			Foxhome, MN			Lake Lillian, MN		
Ethofumesate[a]	Root yield	Sucrose content	Rec. suc.[b]	Root yield	Sucrose content	Rec. suc.	Root yield	Sucrose content	Rec. suc.
--kg ha^{-1}--	kg ha^{-1}	-%-	-kg ha^{-1}-	kg ha^{-1}	-%-	-kg ha^{-1}-	kg ha^{-1}	-%-	-kg ha^{-1}-
Untreated Control	62,100	18.5	10,945	52,000	14.4 b	6,297	78,900	16.8	11,283
Sequential[c]	62,800	18.5	10,974	50,200	14.8 a	6,293	78,700	16.8	11,431
June 15 at 4.48	63,400	18.4	11,089	50,000	14.9 a	6,340	78,000	16.6	11,168
July 15 at 4.48	63,200	18.4	11,040	50,700	14.6 ab	6,284	-	-	-
Aug 15 at 4.48	61,700	18.4	10,741	50,700	14.3 b	6,182	80,900	16.7	11,623
LSD (0.05)	NS	NS	NS	NS	0.37	NS	NS	NS	NS
	--P-value--								
	0.8144	0.7295	0.8001	0.5268	0.0010	0.9225	0.1753	0.6291	0.1713

[a]June, July, and August timings simulated 11-, 10-, and 9-month intervals. Additional treatment information is referenced in Table 4.4.
[b]Recoverable sucrose reported in kilogram per hectare.
[c]Application of 1.12 kg ethofumesate ha^{-1} made every two weeks starting at the 2-lf sugarbeet stage until July 15.

There were no differences in root yield (P=0.5812), sucrose content (P=0.5230) or recoverable sucrose (0.2547) attributed to ethofumesate time of application when data were combined across environments (Table 4.8). Sucrose content was numerically greater 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) or July 15 (10-month interval) compared with the untreated control or 4.48 kg ethofumesate ha^{-1} applied August 15 (9-month interval).

Table 4.8. Root yield, sucrose content, and recoverable sucrose for sugarbeet in response to timing of ethofumesate application, across environments in 2017.

Ethofumesate[a]	Root yield	Sucrose content	Recoverable sucrose
---------kg ha^{-1}--------	---kg ha^{-1}---	---%---	--kg ha^{-1}--
Untreated Control	64,300	16.6	9,500
Sequential[b]	63,600	16.7	9,560
June 15 at 4.48	63,600	16.6	9,540
July 15 at 4.48	64,800	16.6	9,640
Aug 15 at 4.48	63,400	16.4	9,360
LSD (0.05)	NS	NS	NS
	------------------------------	P-value	----------------------------
	0.5812	0.5230	0.2547

[a]June, July, and August timings simulated 11-, 10-, and 9-month intervals. Additional treatment information is referenced in Table 4.4.
[b]Application of 1.12 kg ethofumesate ha^{-1} made every two weeks starting at the 2-lf sugarbeet stage until July 15.

Rotational Crop Tolerance

Corn, dry bean, soybean, and wheat planted in 2018 were timed to simulate a 9-, 10- and 11-month rotation intervals between ethofumesate application and rotational crop seeding. Corn, dry bean, soybean and wheat emergence, growth and development were not affected by residues of ethofumesate (Figure 4.1 and 4.2). Neither a single 4.48 kg ethofumesate ha^{-1} application nor four repeat 1.12 kg ethofumesate ha^{-1} applications affected stand density establishment or stature reduction at any environment.

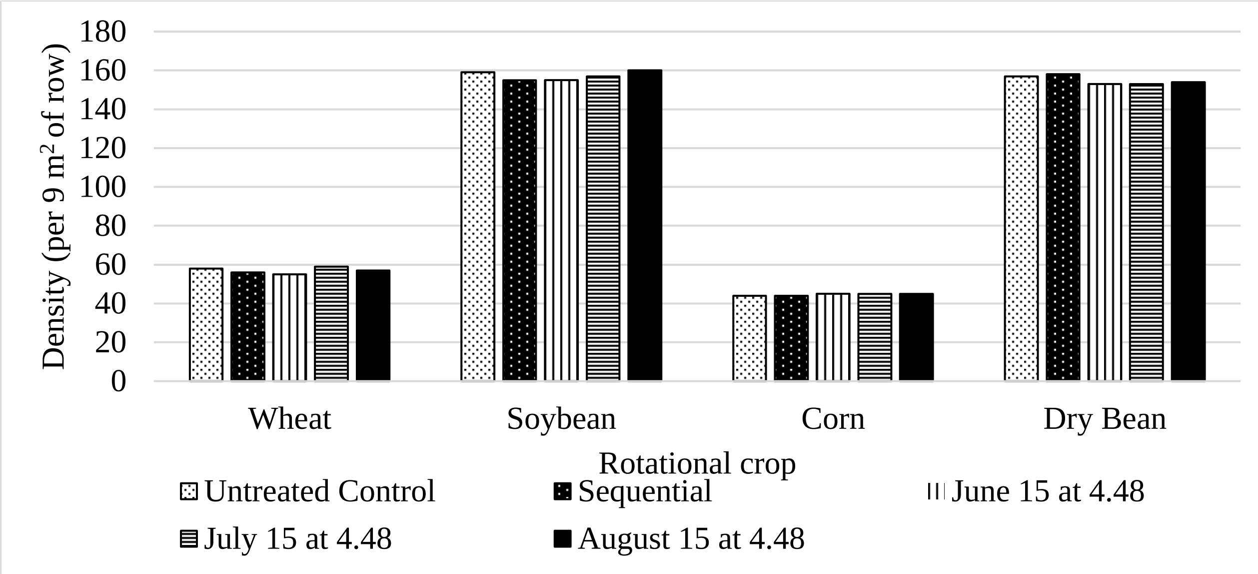

Figure 4.1. Corn, dry bean, soybean, and wheat stand density in response to 2017 timing of ethofumesate application and rate, across environments in 2018.

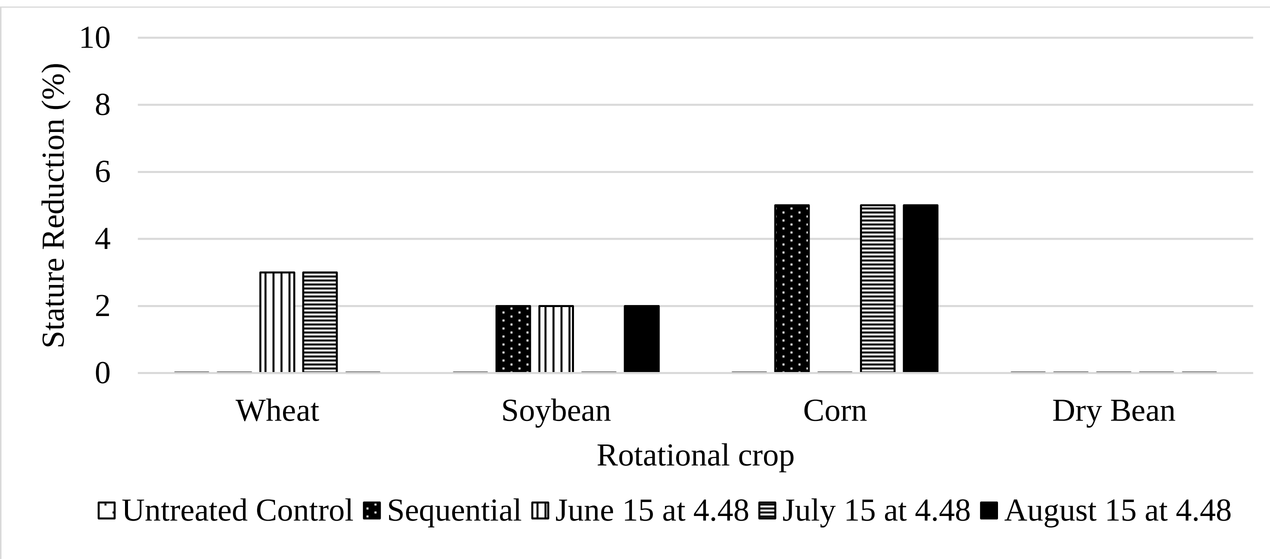

Figure 4.2. Corn, dry bean, soybean, and wheat visible percent stature reduction in response to 2017 timing of ethofumesate application and rate, across environments in 2018.

Corn yield components were not negatively affected by ethofumesate rate and application timing (Table 4.9). Grain moisture was less when corn was seeded 10- or 9-month after a single 4.48 kg ethofumesate ha^{-1} application compared with the untreated control or sequential ethofumesate application. Additionally, corn height at harvest was the same across ethofumesate applications (data not presented).

Table 4.9. Corn test weight, percent moisture, and grain yield in 2018 in response to 2017 ethofumesate treatment.

	Across environments[a]			Crookston, MN		
Ethofumesate[b]	Test weight	Moisture	Grain yield	Test weight	Moisture	Grain yield
-------kg ha^{-1}------	--kg hL^{-1}[c]--	--%--	--kg ha^{-1}[d]--	--kg hL^{-1}--	--%--	-kg ha^{-1}-
Untreated Control	68.5	18.4	14,600	77.1	15.5	8,580
Sequential[e]	68.1	18.4	14,300	78.3	16.5	9,430
June 15 at 4.48	69.0	18.3	14,200	77.0	15.6	9,800
July 15 at 4.48	68.6	18.2	14,400	77.3	15.2	8,600
Aug 15 at 4.48	69.1	17.9	14,400	78.3	16.1	8,580
LSD (0.05)	NS	NS	NS	NS	NS	NS
	----------------------------------P-value---------------------------					
	0.5551	0.3129	0.6269	0.6547	0.5207	0.7787

[a]Prosper, ND, Foxhome, MN, Lake Lillian, MN, Richville, MI.
[b]June, July, and August timings simulated 11-, 10-, and 9-month intervals. Additional treatment information is referenced in Table 4.4.
[c]kilogram per hectoliter.
[d]kilogram per hectare.
[e]Application of 1.12 kg ethofumesate ha^{-1} made every two weeks starting at the 2-lf sugarbeet stage until July 15.

Corn yield from Crookston, MN was not included in the combined environment 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 environments. Corn grain moisture was affected by herbicide treatment in Richville, MI (Figure 4.3). Corn grain averaged 15.7% moisture following a 10- or 9-month interval between application and seeding compared with 16.5% in the untreated check plots when analyzed singly.

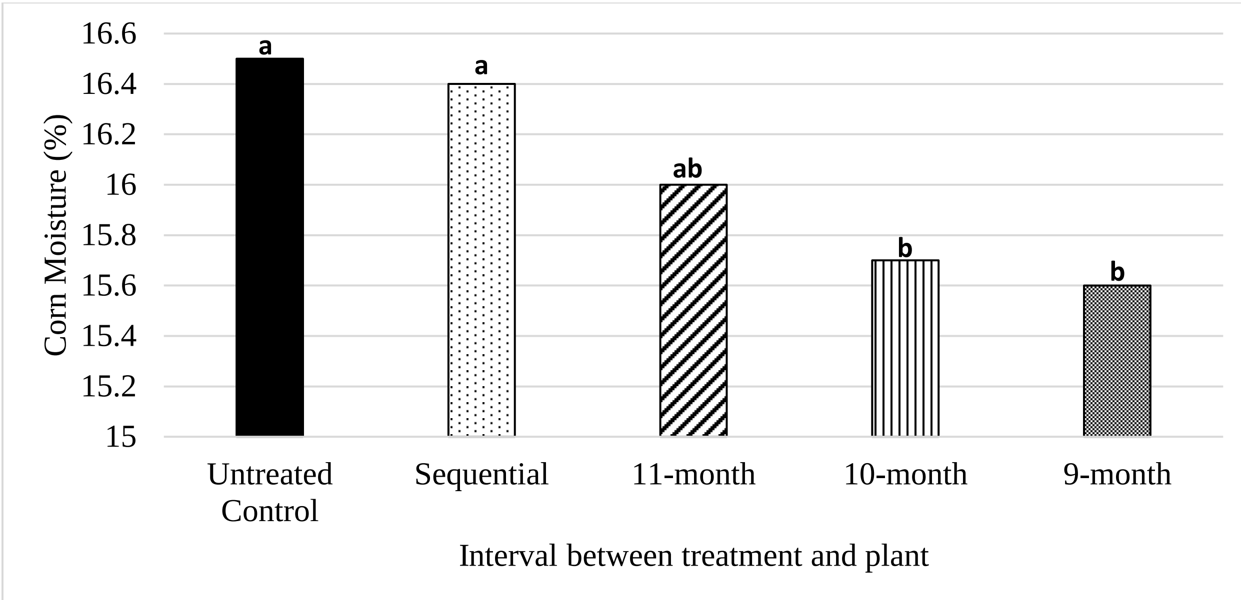

Figure 4.3. Response of corn percent moisture to ethofumesate residues, Richville MI, 2018. Means within a main effect column not sharing any letter are significantly different by the LSD at the 5% level of significance. See Table 1 for treatment reference.

Soybean yield was not affected by ethofumesate rate or 9-, 10-, or 11-month interval between application and seeding across environments (Table 4.10). Soybean yield data from Crookston, MN and Prosper, ND were evaluated separately due to hail in June and September, respectively, which decreased the yield by approximately 1,800 kg ha^{-1}.

Table 4.10. Ethofumesate sugarbeet crop residue impact on soybean yield components in 2018.

Treatment[a]	Foxhome, MN; Lake Lillian, MN; Richville, MI			Prosper, ND; Crookston, MN		
	Test weight	Moisture	Grain yield	Test weight	Moisture	Grain yield
------kg ha^{-1}-----	--kg hL^{-1b}--	--%--	--kg ha^{-1c}--	--kg hL^{-1}--	--%--	--kg ha^{-1}--
Untreated Check	67.9	13.3	4,280	69.3	13.6	2,560
Sequential[d]	67.3	13.2	4,400	68.5	13.6	2,560
June 15 at 4.48	67.8	13.2	4,300	68.0	13.6	2,480
July 15 at 4.48	67.6	13.3	4,200	68.3	13.6	2,630
Aug 15 at 4.48	69.0	13.3	4,500	68.5	13.5	2,460
LSD (0.05)	NS	NS	NS	NS	NS	NS
	--------------------------------------P-value------------------------------------					
	0.0896	0.0659	0.1078	0.3114	0.6116	0.6102

[a]June, July, and August timings simulated 11-, 10-, and 9-month intervals. Additional treatment information is referenced in Table 4.4.
[b]kilogram per hectoliter.
[c]kilogram per hectare.
[d]Application of 1.12 kg ethofumesate ha^{-1} made every two weeks starting at the 2-lf sugarbeet stage until July 15.

Dry bean did not display any growth or developmental effects from ethofumesate throughout the growing season at Richville, MI (data not presented). Moisture and yield, when averaged across treatment, were 15% and 2,100 kg ha^{-1}, respectively.

Wheat yield components were not affected by ethofumesate rate or interval between ethofumesate application and wheat seeding date (Figure 4.4). Difference in wheat grain yield between ethofumesate treatment (rate and application timing) and untreated check were plotted by environment since previous research indicated soil type and rainfall affected ethofumesate fate and persistence in soil (Schroeder and Dexter 1979; Schweizer 1976) (Figure 4.5). There was more treatment variability in wheat grain yield at the Foxhome, MN location than at the other environments.

Rainfall at Foxhome, MN was greater than rainfall at Crookston, MN and Prosper, ND but was less than rainfall at Lake Lillian, MN (Table 4.3). 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 with Prosper or Crookston.

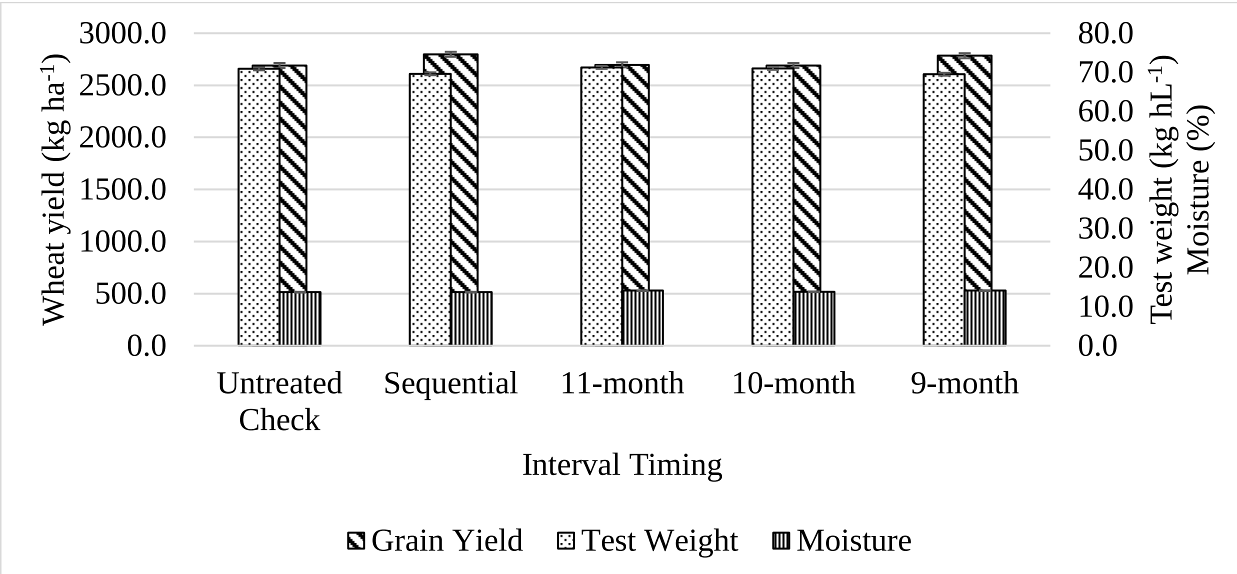

Figure 4.4. Wheat yield, moisture, and test weight in response to prior year ethofumesate rate and timing of ethofumesate application, averaged across environments, 2018. See Table 1 for treatment reference.

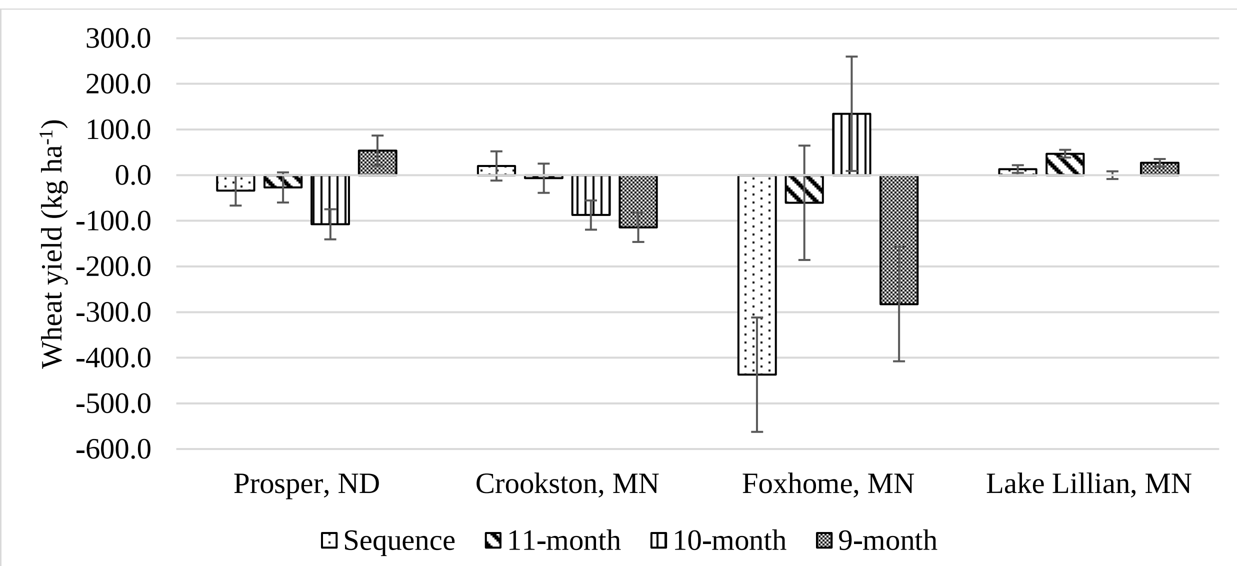

Figure 4.5. Wheat grain yield difference (untreated check – treatment) and standard error of the mean (error bars), across environments, 2018. See Table 1 for treatment reference.

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} application 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 with 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 residue 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 and 2018 which could have aided in the degradation of residual ethofumesate.

Degradation of ethofumesate in soil is related to the action of soil microorganism 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 weeks (Ekins and Cronin 1972) and has a half-life in a sandy loam or a loam soil of 7.7 or 12.6

weeks, 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 with 51 days in bare soil. The authors attributed shorter half-life to increased microbial activity in turfgrass thatch, resulting in greater ethofumesate degradation before it moved in 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 applications (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.

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; Schweizer 1976). 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 five environments in Michigan, Minnesota, and North Dakota in one year.

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CHAPTER 5. SUMMARY

Ethofumesate 4SC Safety

Ethofumesate applied postemergence at rates ranging from 0.28 to 2.24 kg ha^{-1} did not influence sugarbeet density, root yield, or sucrose content in experiments conducted at multiple environments. These results were consistent with the rotational study conducted in 2017 on sugarbeet. However, ethofumesate significantly reduced sugarbeet stature and recoverable sucrose content at 4.48 kg ha^{-1} when sugarbeet tolerance experiments were combined across environments. Differences in results between the two experiments was attributed to greater replication in the sugarbeet tolerance experiments compared with the rotational crop tolerance experiments. Ethofumesate significantly reduced sugarbeet stature at rates greater than 2.24 kg ha^{-1}; however, stature reduction decreased as days after treatment application increased.

Ethofumesate 4SC Efficacy

Ethofumesate alone controlled common lambsquarters, redroot pigweed, and waterhemp up to 84%, 76%, and 84%, respectively; and thus, cannot be classified as an effective POST herbicide and is not recommended to be applied alone for postemergence control. However, ethofumesate did increase efficacy of postemergence glyphosate applications. Glyphosate plus ethofumesate at 1.12 kg ha^{-1} applied early postemergence provided the best overall control of common lambsquarters, redroot pigweed, and waterhemp compared with other herbicide treatments alone or in mixtures in this experiment. Results suggest mixing ethofumesate with glyphosate early postemergence for immediate and residual control of common lambsquarters, redroot pigweed, and waterhemp compared with ethofumesate or glyphosate alone. Benefits of adding ethofumesate to an early postemergence glyphosate application to control common lambsquarters and redroot pigweed may not be observed until later in the growing season since ethofumesate provides season long control. Benefits of ethofumesate may not be observed if application is not timed to an activating rainfall. Additional research may be conducted to evaluate repeat glyphosate and ethofumesate treatments which may buffer the effects of untimely rainfall.

Ethofumesate 4SC Rotational Crop Safety

Previous studies report ethofumesate residue damaged rotational crops, especially wheat and barley. Previous research was conducted on bare soil, whereas our experiment was conducted over sugarbeet canopy. 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 to 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 corn, dry bean, soybean, and wheat grown in sequence with sugarbeet in experiments conducted in Michigan, Minnesota, and North Dakota. Future research should investigate fate of ethofumesate applied POST, especially if new labeled uses for ethofumesate are adopted by growers.