POSTEMERGENCE EFFICACY OF PYROXASULFONE AT DIFFERENT RATES AND TIMINGS IN WHEAT

A Thesis
Submitted to the Graduate Faculty
of
North Dakota State University
of Agricultural and Applied Sciences

By

Codee Zebedee Lee

In Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE

Major Department:
Plant Sciences

April 2018

Fargo, North Dakota

North Dakota State University
Graduate School

Title

Postemergence Efficacy of Pyroxasulfone at Different Rates and Timing in Wheat

By

Codee Zebedee Lee

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. Kirk A. Howatt
Chair

Dr. Richard K. Zollinger

Dr. Tom DeSutter

Dr. Grant Mehring

Approved:

October 25, 2018	Dr. Richard D. Horsley
Date	Department Chair

ABSTRACT

Pyroxasulfone is a VLCFA inhibitor labeled to control grasses and small-seeded broadleaf weeds. Little information is available regarding this herbicide being applied postemergence. Two field experiments were conducted to evaluate the efficacy of pyroxasulfone used postemergence. Pyroxasulfone applied to 2-leaf wheat controlled up to 83% of the green foxtail but had little to no effect on broadleaves. An additional field study was conducted to determine if pyroxasulfone could give supplemental green foxtail control when tank-mixed with ALS inhibitors. Few tank-mix combinations increased control, and the tank-mixes that did had inadequate control, <70%. Greenhouse experiments were also conducted. The first concluded that a wide range of grass species are susceptible to pyroxasulfone applied postemergence. The second demonstrated weed control with pyroxasulfone is almost exclusively due to root uptake. Contradicting levels of control between field and greenhouse experiments suggests more information is needed before pyroxasulfone can be utilized as a postemergence herbicide.

ACKNOWLEDGEMENTS

I would like to express my sincere thanks to my advisor, Dr. Kirk Howatt for his support, assistance, encouragement, and knowledge he shared with me during my time in graduate school. I would also like to thank Ron Roach, Mark Cernia, Sandy Mark, Janet Davidson-Harrington, and Morgan Hanson for their time, support, and friendship they provided during field and greenhouse research. It was a pleasure working alongside all of you.

I would also like to acknowledge and thank my graduate committee, Dr. Richard Zollinger and Dr. Tom DeSutter, for their expertise advice and time spent towards the completion of my thesis. I would also like to thank Dr. Grant Mehring for his help and support with the statistical analysis portion of my thesis. Thank you, North Dakota State University, and the Department of Plant Sciences for accepting me into the program and providing me with facilities, funding, and equipment.

I must also thank my fellow coworkers and graduate students who made my time at NDSU an unforgettable experience: Devin Wirth, Jason Adams, Kelly Satrom, Joe Mettler, Nicholas Schimek, John Breker, Meyer Bohn, and Peder Schmitz.

Furthermore, I would like to thank my parents, Curt and Suzy Lee, and the rest of my family for all their support and encouragement they have given me throughout my life. Without their support, I would not have become the person I have become today.

TABLE OF CONTENTS

LIST OF TABLES

INTRODUCTION AND JUSTIFICATION

Herbicide-resistant weeds have become an increasingly predominant problem every year. Increased number of weeds with resistance to multiple sites of action, has reduced weed control options for crop producers. This is problematic for producers from a sustainability standpoint because the available options are either more expensive or less effective, either of which can reduce profit. New options identified for weed control can maximize production and profitability.

Pyroxasulfone is a very long chain fatty acid inhibitor herbicide labeled to control grasses and small-seeded broadleaf weeds when applied as a preemergence herbicide. Limited research indicates this product demonstrates activity on some emerged plant species. New weed control options may result by characterizing how and what pyroxasulfone controls. Additional information pertaining to this product will be beneficial for determining pyroxasulfone phytotoxicity in crops, weed control spectrum, and environmental influences. All of this information could maximize the utility of this product.

LITERATURE REVIEW

Pyroxasulfone

Pyroxasulfone, sold as Zidua® (BASF Corporation, 26 Davis Drive, Research Triangle Park, NC 27709), is a soil-applied herbicide for selective control of grasses and small-seeded broadleaf weeds. Kumiai Chemical Research Institute Co., Ltd. (Shizuoka, Japan) first discovered and developed pyroxasulfone and later licensed it to BASF, Valent, and FMC (Shaner et al. 2014). Pyroxasulfone has a molecular weight of 391 g mol^{-1}, a melting point of 131 ºC, vapor pressure of 2.4 X 10^{-6} Pa (25 ºC), and water solubility of 3.49 mg L^{-1} (20 ºC). Pyroxasolfone is a Group 15 herbicide that reduces the biosynthesis of very long chain fatty acids (VLCFAs) and acts on emerging seedlings by blocking lipid biosynthesis through inhibition of several VLCFA elongases (Busi et al. 2014). Due to the mechanism of control, pyroxasulfone has little effect on seed germination, and most of the control is believed to come from inhibition of shoot elongation in germinated seeds. Most susceptible weeds will fail to emerge from the soil. However, susceptible grasses that do emerge will appear twisted and malformed with leaves tightly rolled in the whorl and unable to unroll normally. Susceptible broadleaf seedlings that emerge usually have cupped and crinkled leaves and shortened leaf midribs causing a drawstring appearance (Shaner et al. 2014).

The herbicide's unique physical and chemical properties provide an advantageous environmental and toxicological profile (Kumiai Chemical industry co., ltd). Pyroxasulfone has shown selectivity in several agronomic crops and is registered in the United States for use in soybean (*Glycine max*), corn (*Zea mays*), wheat (*Triticum spp.*), and cotton (*Gossypium hirsutum L.*). The herbicide site of action (VLCFA inhibitor) allows for the control of troublesome weeds including weeds resistant to glyphosate, acetolactate synthesis (ALS) inhibitors, and acetyl CoA carboxylase (ACCase) inhibitors (Shaner et al. 2014). Pyroxasulfone is registered to be applied either in the fall, early preplant, or early postemergence, which allows for flexibility in weed control strategy.

Pyroxasulfone is labeled to control various grasses and small-seeded broadleaf weeds. Barnyardgrass (*Echinochloa crus-galli* (L.) Beauv.), downy brome (*Bromus tectorum* L.), green foxtail (*Setaria viridis* (L.) Beauv.), yellow foxtail (*Setaria pumila* (L.) Beauv.), wild oat (*Avena fatua* L.), eastern black nightshade (*Solanum ptychanthum* Dun.), redroot pigweed (*Amaranthus retroflexus* L.), and waterhemp (*Amaranthus rudis* Sauer) are weeds either controlled or suppressed in North Dakota (Zidua product label 2015).

Pyroxasulfone Environmental Influences

Preemergence herbicides are applied to the soil and require movement into the soil profile by means of rainfall or irrigation. According to the pyroxasulfone product label, this herbicide requires at least 1.27 cm of rainfall or irrigation before weeds germinate and emerge for control. With the appropriate amount of rainfall, herbicide active ingredient becomes present in the soil solution and is then available to the seedlings as they absorb water. Therefore, dry conditions result in decreased plant exposure to the herbicide. Without appropriate rainfall and soil moisture, the effectiveness of pyroxasulfone and other soil-applied herbicides decreases. According to Hager and Sprague (2001), there is no absolute defined amount of rainfall, but generally surface-applied herbicides require 1.27 to 2.54 cm of precipitation within 7 to 10 days after application for control.

Pyroxasulfone efficacy is also dependent on soil texture and composition. This is due to the cation exchange capacity (CEC) of the soil, which is dependent on the clay’s mineralogy, its content, and the organic matter content. This is emphasized by the pyroxasulfone herbicide label, as the rate required for adequate weed control increases with fine soil textures. According to Walsh et al. (2011), higher rates of pyroxasulfone were required to reduce survival by 50% for soils with higher clay content than were required on sandier soils. Plant biomass response to pyroxasulfone indicated more clearly the decreased efficacy of pyroxasulfone at lower application rates in soils with both higher clay and organic matter contents. Organic matter exhibited an even greater capacity to adsorb or tie up general soil herbicides than clay (College of Agriculture and life Sciences 2015).

OBJECTIVES

I. Determine efficacy of postemergence pyroxasulfone at different rates and timings to control various key grass and broadleaf weeds.

II. Evaluate wheat response to pyroxasulfone applied postemergence.

III. Determine weed control enhancement of pyroxasulfone when applied postemergence with different adjuvants.

IV. Evaluate weed control efficacy of pyroxasulfone when tank-mixed with various ALS-inhibiting herbicides.

V. Evaluate soil vs. foliar effects of pyroxasulfone on various grass species.

MATERIALS AND METHODS

Pyroxasulfone Control Postemergence in Wheat

Field experiments to evaluate postemergence efficacy of pyroxasulfone on various weed species in wheat, as well as wheat response, were conducted in 2015 near Prosper and Fargo, North Dakota. The Fargo soil was a Fine, smectic, frigid Typic Epiaquert, and the Prosper soil was a mix between a fine-silty, mixed, superactive, frigid typic endoaquol and a fine-silty, mixed superactive, frigid Aeric Calciaquol (Table 17). Each experimental unit, or plot, was 3 m wide by 9 m long. The spring wheat (*Triticum* spp.) cultivar, Prosper (Mergoum et al. 2012), was used across all sites and was planted at 2,470,000 seeds ha^{-1} with a small drill planter (3P600 Great Plains, 1525 E North Street Salina, KS 67401). Treatments were applied the length of the plot to the center 2 m with a CO_2-pressurized backpack sprayer and boom system. The boom system included four TurboTee 11001 (TeeJet, Spraying Systems Co. 200 W. North Ave, Glendale Heights, IL 60139) nozzle tips spaced 51 cm apart. Treatments were applied at a speed of 5 km hr^{-1} with 276 kPa of pressure that delivered 80 L ha^{-1}.

Table 1. Soil series descriptions for Fargo and Prosper, ND.

Location	Soil Series [a]	Slope	Texture	OM	pH
		---%---		---%---	
Fargo 1	Fargo (NW-22)	0-2	Silty Clay Loam	6.8	7.2
Fargo 2	Fargo (Campus)	0-2	Silty Clay Loam	6.0	7.5
Prosper	Kindred/Bearden	0-2	Loam	3.5	7.3
Mineral Soil			Sandy Loam	3.9	7.4

[a]Soil series obtained from (USDA-NRCS, 2016).

Two field experiments were conducted in 2015. The first study included pyroxasulfone applied alone and mixed with different adjuvants at a single application timing applied to weed seedlings approximately 3-4 cm tall (Table 1). Nine adjuvant systems were mixed with pyroxasulfone: ammonium sulfate liquid (AMS-L), nonionic surfactant (NIS), NIS + AMS-L, petroleum oil (PO), PO + AMS-L, methylated seed oil (MSO), MSO + AMS-L, high surfactant methylated oil concentrate (HSMOC), and HSMOC + AMS-L. The second study included pyroxasulfone applied with different rates at different timings. The second study evaluated three application timings with four pyroxasulfone rates in a factorial combination of treatments (Table 2). The four rates used were 63, 119, 182, and 238 g ai ha^{-1}, and application timings were 2, 3, and 5-leaf wheat. Environmental conditions for each herbicide application were recorded (Table 3).

Table 2. Pyroxasulfone mixed with adjuvants treatment list.

Treatment	Herbicide rate	Adjuvant rate
	-g ai ha^{-1}-	-ml ha^{-1}-
Untreated	-	-
Pyroxasulfone	119	-
Pyroxasulfone + AMS-L[a]	119	2%
Pyroxasulfone + NIS[b]	119	0.25%
Pyroxasulfone + NIS + AMS-L	119	0.25% + 2%
Pyroxasulfone + PO[c]	119	1754
Pyroxasulfone + PO + AMS-L	119	24 + 0.25%
Pyroxasulfone + MSO[d]	119	1754
Pyroxasulfone + MSO + AMS-L	119	24 + 2%
Pyroxasulfone + HSMOC[e]	119	1461
Pyroxasulfone + HSMOC + AMS-L	119	1461

[a] Ammonium sulfate-liquid.
[b] Nonionic surfactant.
[c] Petroleum oil.
[d] Methylated seed oil.
[e] High surfactant methylated oil concentrate.
[f] %, percent based on volume/volume.

Table 3. Pyroxasulfone herbicide rate and timing treatment list.

Treatment	Herbicide rate	Adjuvant rate[a]	Application timing
	-g ai ha^{-1}-	-ml ha^{-1}-	wheat stage
Untreated	-	-	-
Pyroxasulfone + MSO[a]	63	1461	2-leaf
Pyroxasulfone + MSO	119	1461	2-leaf
Pyroxasulfone + MSO	182	1461	2-leaf
Pyroxasulfone + MSO	238	1461	2-leaf
Pyroxasulfone + MSO	63	1461	3-leaf
Pyroxasulfone + MSO	119	1461	3-leaf
Pyroxasulfone + MSO	182	1461	3-leaf
Pyroxasulfone + MSO	238	1461	3-leaf
Pyroxasulfone + MSO	63	1461	5-leaf
Pyroxasulfone + MSO	119	1461	5-leaf
Pyroxasulfone + MSO	182	1461	5-leaf
Pyroxasulfone + MSO	238	1461	5-leaf

[a] Methylated seed oil.

Table 4. Environmental data recorded at pyroxasulfone application for rate and timing experiments in Fargo and Prosper, ND locations in 2015.

Location	Factor	Weed Stage (cm)		
		1	2	3
Fargo 1				
Campus	Crop Stage	2 leaf	3 leaf	5 leaf
	Application Date	5/20/15	6/4/15	6/10/15
	Application Time	11:19am	12:07pm	2:48pm
	Air temperature (ºC)	18	21	27
	Soil temperature (ºC)	10	14	21
	Dew point (ºC)	3	17	13
	Relative humidity (%)	38	76	42
	Wind speed (km hr^{-1})	10	11	10
	Wind direction (º)	225	20	330
	Cloud cover	Clear	Clear	80%
	Soil surface moisture	Moist	Damp	Dry
Fargo 2				
NW-22	Crop Stage	2 leaf	5 leaf	6 leaf
	Application Date	5/28/15	6/10/15	6/19/15
	Application Time	2:35pm	2:05pm	9:55am
	Air temperature (ºC)	29	23	18
	Soil temperature (ºC)	21	21	17
	Dew point (ºC)	10	16	23
	Relative humidity (%)	31	58	100
	Wind speed (km hr^{-1})	2	6	16
	Wind direction (º)	300	5	135
	Cloud cover	10%	40%	10%
	Soil surface moisture	Moist	Dry	Dry
Fargo 3				
NW-22	Crop Stage	2 leaf	3 leaf	4 leaf
	Application Date	5/28/15	6-5-15	6/10/15
	Application Time	1:45pm	9:32am	2:15pm
	Air temperature (ºC)	27	17	23
	Soil temperature (ºC)	21	15	21
	Dew point (ºC)	9	17	16
	Relative humidity (%)	37	100	58
	Wind speed (km hr^{-1})	5	4	5
	Wind direction (º)	350	115	330
	Cloud cover	15%	100%	Clear
	Soil surface moisture	Moist	Damp	Dry
Prosper				
	Crop Stage	2 leaf	3 leaf	5 leaf
	Application Date	5/22/15	6/4/15	6/10/15
	Application Time	8:20am	9:40am	12:48pm
	Air temperature (ºC)	16	18	24
	Soil temperature (ºC)	10	12	20
	Dew point (ºC)	6	9	14
	Relative humidity (%)	46	55	53
	Wind speed (km hr^{-1})	2	18	5
	Wind direction (º)	180	5	350
	Cloud cover	Clear	Clear	95%
	Soil surface moisture	Moist	Dry	Dry

Wheat phytotoxicity and weed control ratings were recorded for all trials 2, 4, and 6 weeks after treatment application. Phytotoxicity, or visible injury ratings of wheat, was evaluated on a 0 to 100 scale, with 0 for no visible damage and 100 as complete plant death. Visible injury included stunting, chlorosis, necrosis, and overall injury observed. Herbicide efficacy ratings were also conducted on a 0 to 100 scale, with 0 being no weed control and 100 being completely weed free. Damage to the weeds included stunting, chlorosis, necrosis, and plant death. Foxtail populations in the rate/timing studies were determined by counting foxtail plants in two 0.1-m^2 quadrats per plot. Counts were averaged across the subsamples at the end of the growing season. Yield data were not collected due to confounded crop response from insufficient weed control.

All trials were conducted in randomized complete block design (RCBD) with four replicates. Data were subject to analysis of variance using SAS (Statistical Analysis Software 2003, version 9.1, SAS Institute, Inc., 100 SAS Campus Drive, Cary, NC 27513). Trial location, herbicide treatment, and application timing were treated as fixed effects. Evaluation timing and weed species were analyzed as independent experiments. Means were separated with Fisher's F-protected LSD at α=0.05.

Species Screening

Eight troublesome grass weeds were used to evaluate the spectrum of control for pyroxasulfone as a postemergence treatment. The species included wild oat (*Avena fatua* L.), green foxtail (*Setaria viridis* (L.) Beauv.), yellow foxtail (*Setaria pumila* (L.) Beauv.), barnyardgrass (*Echinochloa crus-galli* (L.) Beauv.), downy brome (*Bromus tectorum* L.), Japanese brome (*Bromus japonicas* Thunb. Ex Murr.), Persian darnel (*Lolium persicum* Boiss. And Hohen. Ex Boiss.), and foxtail barley (*Hordeum jobatum* L.).

Sandy loam soil (S&S Landscaping Co., Inc. 2777 Fiechtner Dr. S, Fargo, ND 58103) with a pH of 7.4 and OM content of 3.9% (Table 17) was placed in pots 10-cm by 15-cm by 5-cm deep (TO plastics 450, 830 Cty Rd 75, Clearwater, MN 55320) at seeding. All species, except wild oat, were seeded at high populations to ensure adequate germination, and thinned to 25 plants per pot at emergence. Wild oat seed required scarification for germination. Seeds were de-hulled, placed in petri dishes lined with Whatman No. 9 filter paper (GE Healthcare Amersham Place Little Chalfont, Buckinghamshire, UK) and saturated with distilled water. Petri dishes were incubated in the dark at 5 °C for 24 h. Wild oat seeds were then pierced with a sterile needle, re-saturated with distilled water, and incubated for an additional 48 h at 5 °C. After incubation, 30 wild oat seeds were placed in pots and thinned to 20 plants per pot after germination. Natural light was supplemented with 430-watt high pressure sodium lamps (Phillips lighting company, 200 Franklin Square Drive, Somerset, NJ 08873-6800) set to a 16-h photoperiod. Individual pots were watered daily with distilled water to prevent excessive drying of soil. Liquid fertilization with Micacle-Gro ([24-8-16] Miracle-Gro Products Inc. P.O. Box 267, Marysville, OH 43041) at 3 g L^{-1} was applied one week prior to herbicide application to avoid nutrient deficiencies.

Treatment application was performed using a chamber sprayer (Research Track Sprayer. DeVries Manufacturing, Hollandale, MN. Serial number SB8-095) at the one-leaf stage with a TurboTee 8001E flat fan nozzle (TeeJet, Spraying Systems Co. 200 W. North Ave, Glendale Heights, IL 60139). The sprayer delivered 94 L ha^{-1}, with a nozzle height of 37 cm, pressure of 276 KPa, and speed of 4 km h^{-1}. Pyroxasulfone was applied at 0, 119, and 238 g ha^{-1}. Individual pots were randomized weekly to minimize microenvironment effects.

Efficacy ratings were evaluated as previously stated on each of the eight grass species with evaluations 2 and 4 weeks after treatment. Remaining aboveground biomass was harvested 4 weeks after treatment, placed in a drier at 43 ^{o}C for 7 days, and dry weights were measured with a GX-200 balance (Data Support Company, 14639 Arminta Street Panorama City. Serial number 14561163).

Grass species and evaluation timing were treated as independent studies. Each of the eight grass species were treated as separate experiments conducted as completely randomized designs (CRD). Each CRD included three treatments with four replications and repeated. Analysis of variance was conducted with SAS. Means separation was performed with Fisher's F-protected LSD at α=0.05.

Pyroxasulfone in Tank-Mix

Studies were established in 2016 near Prosper and Fargo, North Dakota. Cultivar, planting, and spray application techniques were the same as experiments in 2015 previously described. Foxtail was the target grass species used.

This study included pyroxasulfone in tank-mix with acetolactate synthase (ALS) inhibitors. Flucarbazone, theincarbazone, pyroxsulam, and propoxycarbazone were tank-mixed with pyroxasulfone at both the 119 and 238 g ai ha^{-1} (1X and 2X rates) in a factorial combination of treatments (Table 4). Herbicides applied alone, along with an untreated check, provided a comparison to determine whether additive or synergistic effects were achieved when tank mixing pyroxasulfone in combination with ALS inhibitor herbicides. Broadleaf weeds were controlled with a broadcast treatment of 88 ml ae ha^{-1} MCPAe, 30 ml ha^{-1} fluroxypyr acid, 16 ml ae ha^{-1} clopyralid acid (Weld), and 77 ml ae ha^{-1} NIS. Environmental conditions for herbicide applications are listed in table 5.

Table 5. Pyroxasulfone as a tank-mix with ALS inhibitors treatment list.

Treatment	Herbicide rate
	-g ai ha^{-1}-
Untreated	-
Pyroxasulfone	119
Pyroxasulfone	238
Pyroxasulfone + flucarbazone	119 + 22
Pyroxasulfone + flucarbazone	238 + 22
Pyroxasulfone + thiencarbazone	119 + 5
Pyroxasulfone + thiencarbazone	238 + 5
Pyroxasulfone + pyroxsulam	119 + 15
Pyroxasulfone + pyroxsulam	238 + 15
Pyroxasulfone + propoxycarbazone	119 + 10
Pyroxasulfone + propoxycarbazone	238 + 10
Flucarbazone	22
Thiencarbazone	5
Pyroxulam	15
Propoxycarbazone	10

Table 6. Environmental data recorded at pyroxasulfone tank-mix application in Fargo and Prosper, ND locations in 2016.

Factor	Fargo	Prosper
Crop Stage	3 Leaf	3 Leaf
Application Date	6/2/16	6/7/16
Application Time	9:07 am	10:20 am
Air temperature (ºC)	19	20
Soil temperature (ºC)	12	17
Dew point (ºC)	8	7
Relative humidity (%)	49%	43%
Wind speed (km hr^{-1})	10	8
Wind direction (º)	270	360
Cloud cover	Clear	Clear
Soil surface moisture	Dry	Dry

Application procedures were conducted as previously stated. Data collected included phytotoxicity, efficacy, foxtail populations, and wheat yield. Phytotoxicity of wheat was evaluated on a 0 to 100 scale, with 0 representing no visible damage and 100 representing complete plant death. Yellow foxtail and wild oat efficacy ratings were based on a 0 to 100 scale, with 0 representing no damage observed to the grass species and 100 representing grass species being completely controlled. Wild oat pressure was only observed and evaluated at the

Prosper, ND location. Phytotoxicity and efficacy ratings were recorded 2, 4, and 6 weeks after treatment. Populations of yellow foxtail were estimated by counting plants within two 0.1-m^2 quadrats, and then averaged across subsamples. All trials were harvested for grain yield using a plot combine (Hege 125B) with a 1.2-m-wide grain header. Grain samples were cleaned with an Almaco Air Blast Seed Cleaner (Almaco Allan Machinery Company. 99 M Ave., Nevada , IA 50201).

Experiments were laid out as an RCBD with four replicates. Data were subject to analysis of variance using SAS. Trial location, herbicide treatment, and application timing were treated as fixed effects. Evaluation timing and weed species were analyzed as independent experiments. Means were separated with Fisher's F-protected LSD at α=0.05.

Foliar vs. Soil Activity

Green foxtail, downy brome, and wild oat were found to be susceptible in the species screening and were used to determine foliar vs. soil activity of pyroxasulfone. Similar soil to the previous greenhouse study was used. Downy brome and green foxtail populations were planted at high populations, and thinned to 25 plants per pot at emergence. Wild oat seeds were de-hulled, soaked, poked, and thinned to 20 plants per pot as previously described in the species screening experiment. Natural light was supplemented with 430-watt high pressure sodium lamps set to a 16-h photoperiod. Pots were watered daily using distilled water to prevent excessive drying of soil.

Pyroxasulfone at 119 and 238 g ha^{-1} was applied to the foliage alone, soil alone, and a combine foliage and soil application. To evaluate foliar vs. soil effects individual foliar and soil applications were incorporated with a combined foliar and soil application and untreated check for comparison (Table 6). Combined foliar and soil, and foliar alone treatment applications were performed with the same chamber sprayer as previously described in the species screening experiment at the 1-leaf stage with a TurboTee 8001E flat fan nozzle. Foliar applied treatments received a layer of activated charcoal [Charcoal Green® Soil D·Tox (Coal Granular)] placed on top of the soil to adsorb and prevent pyroxasulfone from moving into the soil profile. The sprayer delivered 94 L ha^{-1}, with a nozzle height of 37 cm, pressure of 276 Kpa, and speed of 4 km h^{-1}. Soil alone applications were achieved with a dilution applied with glass beakers at the one leaf stage. Soil applied treatment dilutions were mixed and applied directly to the soil in a serpentine pattern around the plants. Dilutions were calculated as follows:

$$\frac{150\ cm^2}{1\ pot} \times \frac{1\ m^2}{10000\ cm^2} \times \frac{1\ ha}{10000\ m^2} \times \frac{119\ g\ ai}{1\ ha} \times \frac{12\ pots}{1\ exp.} = \frac{0.002142\ \mathrm{g\ ai}}{exp.}$$

$$0.2142\ g\ ai \rightarrow 1000\ ml\ H_2O = \frac{0.0002142\ \mathrm{g\ ai}}{1000\ ml\ solution}$$

$$\frac{10\ ml}{solution} \rightarrow 990\ ml\ H_2O = \frac{0.002142\ \mathrm{g\ ai}}{1000\ ml\ solution}$$

$$\frac{1000\ ml\ solution}{12} = 83.3\ ml\ solution$$

$$1X = \frac{83.3\ ml\ solution}{pot} + \frac{83.3\ ml\ H_2O}{pot}; 2X = \frac{166.6\ ml\ solution}{pot}$$

Pots were randomized weekly to minimize microenvironment effects.

Each species was conducted as a separate experiment and was repeated twice as a CRD with four replications. Applications for foliar treatments and combined foliar and soil treatments were performed as previously stated at the one-leaf stage.

Table 7. Pyroxasulfone foliar vs. soil activity treatment list.

Treatment	Herbicide rate	Herbicide placement
	-g ai ha^{-1}-	
Untreated	-	-
Pyroxasulfone	119	Foliar[a]
Pyroxasulfone	119	Foliar & Soil[b]
Pyroxasulfone	119	Soil[c]
Pyroxasulfone	238	Foliar
Pyroxasulfone	238	Foliar & Soil
Pyroxasulfone	238	Soil

[a] Foliar – pyroxasulfone applied only to the foliage.
[b] Foliar & Soil – pyroxasulfone applied to both soil and foliage.
[c] Soil – pyroxasulfone applied only to the soil.

Efficacy ratings were evaluated the same as previously stated with evaluations taken 14 and 28 days after treatment. Dry weights were collected the same as previously stated. Grass species and evaluation timing were treated as independent studies. Analysis of variance and means separation were conducted the same as previously stated.

RESULTS AND DISCUSSION

Pyroxasulfone Control Postemergence in Wheat

Little information about pyroxasulfone applied postemergence was available. In preliminary research, rate/timing and adjuvant experiments were conducted. The objectives of these studies were to determine the efficacy of postemergence pyroxasulfone at different rates and timings, and evaluate wheat response when pyroxasulfone is applied postemergence. Pyroxasulfone rates used in this study were 63, 119, 182, and 238 g ai ha^{-1}, which represented one-half, full, one and one-half, and double rates for use in wheat (Zollinger et al. 2015). Species separation and evaluation timings were run separately.

Throughout all locations no wheat phytotoxicity was observed at any rate or timing (data excluded). Broadleaf weed control with pyroxasulfone 2 weeks after application was negligible, with the highest control being 33% on wild mustard with 238 g ai ha^{-1} pyroxasulfone (Table 7). Damage expressed 2 weeks after application was negligible 4- and 6-weeks after application (4- and 6-week evaluation data excluded). The initial broadleaf symptomology 2 weeks after application was speckling of the leaf tissue which is not a characteristic symptom of VLCFA inhibitors. The uncharacteristic speckling of the leaf tissue symptomology and ability to overcome and outgrow damage suggests that initial herbicide damage to broadleaf weeds can be attributed to methylated seed oil (MSO) leaf burn.

Table 8. Pyroxasulfone rate and application timing effects on broadleaf control in wheat 2 weeks after application.

Timing	Application	Species[a]				
		wimu[b]	corw[c]	colq[d]	wibw[e]	vema[f]
	-g ai ha^{-1}-	———————————%———————————				
2-leaf						
	63	8g[g]	9c	21c	8ef	13cd
	119	14def	21b	26b	10d	16c
	182	18cd	24b	30b	11cd	25b
	238	23bc	33a	37a	17a	32a
3-leaf						
	63	14de	9c	14de	11cd	7e
	119	15de	8cd	16cd	10cd	7e
	182	26b	9c	14de	12bc	8de
	238	33a	11c	18cd	13b	9de
5-leaf						
	63	8fg	5cd	10e	7f	8de
	119	11efg	4cd	11e	7f	9de
	182	17d	6cd	11e	8ef	9de
	238	26b	5cd	16cd	10de	12cd

[a] Species separation were run independently.
[b] wimu, wild mustard.
[c] corw, common ragweed.
[d] colq, common lambsquarters.
[e] wibw, wild buckwheat.
[f] vema, venice mallow.
[g] Letters in each column represent means separation with Fisher's F protected LSD at α=0.05.

Green foxtail activity was observed at all rates, timings, and locations in 2015 (Table 8). Evaluation timings were analyzed individually. Proxasulfone applied at 238 g ai ha^{-1} to two-leaf wheat had the highest level of green foxtail control at all evaluation timings. Earlier applications resulted in more observable green foxtail control.

Application timing differences in control was more prevalent 6-weeks after application, compared to 2- and 4-weeks after application. Six weeks after application, 238 g ai ha^{-1} pyroxasulfone provided 33% control at the 5-leaf wheat stage, 57% at 3-leaf, and 83% applied to the 2-leaf. Smaller differences in application timing were observed in the earlier foxtail evaluations. Two weeks after application, 238 g ai ha^{-1} pyroxasulfone provided 53%, 64%, and 76% control when applied to 5-leaf, 3-leaf, and 2-leaf wheat, respectively.

Table 9. Pyroxasulfone rate and application timing effects on green foxtail control in wheat 2, 4, & 6 weeks after application.

Timing [a]	Rate	2 WAA [c]	4 WAA	6 WAA
	-g ha^{-1}-	———————	%	———————
2-leaf [b]				
	63	45efg [d]	57cd	61c
	119	57cd	65b	70b
	182	68b	74a	76b
	238	76a	77a	83a
3-leaf				
	63	33h	45e	29ef
	119	48ef	55d	33e
	182	49ed	64bc	45d
	238	64bc	69ab	57c
5-leaf				
	63	37gh	22g	12g
	119	41fgh	27g	13g
	182	46ef	36f	25f
	238	53de	45e	33e

[a] Application timings were treated as separate experiments.
[b] Wheat growth stage at herbicide application.
[c] Weeks after application.
[d] Letters in each column represent means separation with Fisher's F protected LSD at α=0.05.

Pyroxasulfone tended to have more green foxtail control during earlier application timings with higher rates of pyroxasulfone. Earlier applications of pyroxasulfone had higher levels of control, and maintained control longer. A 238 g ai ha^{-1} rate of pyroxasulfone applied to 2-leaf wheat had 76% green foxtail control 2-weeks after application, and 83% control 6-weeks after application. The same treatment applied to 5-leaf wheat had 53% control 2-weeks after application, and 33% control 6-weeks after application. Yamaji et al. (2014) found 100% green foxtail control with 250 g ai ha^{-1} pyroxasulfone 41 days after application when applied pre-emergence. The rate/timing study conducted supports their finding with green foxtail being susceptible to pyroxasulfone. However, the difference in observed control between the two studies was likely due to the preemergence timing reported in the Yamaji et al. (2014) study. This could explain why the rate/timing study observed more green foxtail control when the application timing was closer to a pre-emergence timing, relative to rate. With confirmed green foxtail suppression and lack of activity on broadleaf weeds when applied postemergence, further pyroxasulfone research was focused around grass control.

An adjuvant experiment was also conducted in the summer of 2015. This experiment was conducted to determine if addition of adjuvants increased the efficacy of pyroxasulfone when applied postemergence. Initial leaf burn similar to that of the rate/timing experiment was observed. Initial plant damage was negligible, and adjuvants did not increase efficacy of pyroxasulfone (data not shown).

Species Screening

Herbicide phytotoxicity varies among species. Pyroxasulfone selectivity is attributed to physiological differences in metabolism, which explains why pyroxasulfone can selectively control rigid ryegrass in wheat (Tanetani et al. 2013). The objective of the species screening was to determine a control spectrum of pyroxasulfone useful to North Dakota. Species separation and evaluation timings were run independently.

Grass species indicated differences in efficacy between pyroxasulfone applied at 119 and 238 g ha^{-1} (Table 9). Two weeks after application, pyroxasulfone applied at 238 g ai ha^{-1} provided greater control of wild oat, green foxtail, barnyardgrass, downy brome, Persian darnel, and foxtail barley than pyroxasulfone applied at 119 g ai ha^{-1}. Four weeks after application, pyroxasulfone applied at 238 g ai ha^{-1}, had greater control of wild oat, green foxtail, downy brome, Persian darnel, and foxtail barley than 119 g ai ha^{-1}, however barnyardgrass control was not different between the two rates. Two weeks after application there was no difference in

Persian darnel efficacy, but 4-weeks after application pyroxasulfone applied at 238 g ai ha^{-1} provided more control than 119 g ai ha^{-1}.

Table 10. Species screening efficacy 2 & 4 weeks after application.

		Species [a]						
Rating	Treatment	wioa[b]	grft[c]	bnyg[d]	dobr[e]	jpbr[f]	psdn[g]	foba[h]
	-g ha^{-1}-	—————————————			%	—————————————		
2 WAA								
	119	56b[i]	84b	61b	70b	75a	73b	63b
	238	60a	87a	63a	78a	75a	78a	65a
4 WAA								
	119	54b	83b	72a	79a	69a	61b	60b
	238	56a	90a	73a	81a	71a	65a	64a

[a] Species separation were run independently.
[b] wioa, wild oat.
[c] grft, green foxtail.
[d] bnyg, barnyardgrass.
[e] dobr, downy brome.
[f] jpbr, Japanese brome.
[g] psdn, Persian darnel.
[h] foba, foxtail barley.
[i] Letters in each column represent means separation with Fisher's F protected LSD at α=0.05.

All species' dry biomass decreased from the untreated check when 119 g ai ha^{-1} pyroxasulfone was applied. There was no difference in plant biomass between 119 and 238 g ai ha^{-1} treatments of pyroxasulfone for any specie tested (Table 10) because 1x rate eliminated almost all growth.

Table 11. Species screening dry weights

	Species[a]						
Treatment	wioa[b]	grft[c]	bygr[e]	dobr[f]	jpbr[g]	psdn[h]	foba[i]
-g ai ha^{-1}-				g			
0	1.92a[j]	0.85a	0.71a	0.90a	1.21a	1.48a	0.52a
119	0.50b	0.15b	0.18b	0.09b	0.14b	0.12b	0.06b
238	0.43b	0.07b	0.18b	0.08b	0.12b	0.09b	0.03b

[a] Species separation was ran independently.
[b] wioa; wild oat
[c] grft; green foxtail
[d] yeft; yellow foxtail
[e] bygr; barnyardgrass
[f] dobr; downybrome
[g] jpbr; japanese brome
[h] psdn; Persian darnell
[I] foba; foxtail barley
[j] Letters in each column represent means separation with Fisher's F protected LSD at α=0.05.

This study concluded that a wide range of grass species are susceptible to postemergence pyroxasulfone. Pyroxasulfone provided ≥ 60% control of wild oat, green foxtail, barnyardgrass, downy brome, Japanese brome, Persian darnel, and foxtail barley. In a greenhouse study conducted by Yamaji et al. (2014) 125 g ai ha^{-1} pyroxasulfone applied pre-emergence was able to control 100% of barnyardgrass, green foxtail, giant foxtail, yellow foxtail, johnsongrass, and large crabgrass. Again, the higher level of control observed is likely due to pre-emergence application timing.

Pyroxasulfone in Tank-Mix

ALS-inhibiting herbicides are some of the most commonly used herbicides in the world (Tranel and Wright 2002) with many utilized in cereal production. However, ALS-inhibiting herbicides for use in cereals are often weak on foxtail control. A study conducted by Satchivi et al. (2017) found 15 g ai ha^{-1} of pyroxulam controlled 81% of green foxtail. Green foxtail and yellow foxtail are some of the most troublesome annual grass weeds in cereal crops. A survey conducted in the summer of 2000 by Zollinger et al. (2003) showed green foxtail was the most abundant weed in wheat, and yellow foxtail was the 3rd most abundant. Previous internal research demonstrated green foxtail was susceptible to pyroxasulfone postemergence, however, no broadleaf control was found when pyroxasulfone was applied postemergence. Combinations of pyroxasulfone and ALS-inhibitors could give broad spectrum weed control with supplemental green foxtail. The objective of the second study was to evaluate the efficacy of pyroxasulfone when tank-mixed with various ALS-inhibiting herbicides. Evaluation timings were analyzed individually.

Pyroxasulfone alone applied at both 119 and 238 g ai ha^{-1} had similar or lower levels of green foxtail control, compared to individual and tank-mix combinations that included flucarbazone, thiencarbazone, pyroxulam and propoxycarbazone, throughout all evaluation timings (Table 11). Flucarbazone controlled 54% of green foxtail two weeks after application. Two weeks after application, thiencarbazone applied at 5 g ai ha^{-1} had the greatest green foxtail control with 64%. However, when thiencarbazone was tank-mixed with 119 g ai ha^{-1} pyroxasulfone the green foxtail control decreased to 49%, which is indicative of an antagonistic relationship between the two herbicides. Other than the apparent antagonistic response observed, four and 6-weeks after application, individual or tank-mix combinations that included flucarbazone or thiencarbazone provided the highest control.

Table 12. Pyroxasulfone as a tank-mix with ALS inhibitors control of green foxtail 2, 4 and 6 weeks after application.

Treatment	Herbicide rate	Rating (WAA)		
		2	4	6
	-g ai ha^{-1}-	——————g——————		
Pyroxasulfone	119	37ef[a]	48e	33d
Pyroxasulfone	238	38ef	48e	34d
Pyroxasulfone + Flucarbazone	119 + 22	54b	78ab	70a
Pyroxasulfone + Flucarbazone	238 + 22	54b	82a	77a
Flucarbazone	22	53bc	82a	77a
Pyroxasulfone + Thiencarbazone	119 + 5	49bcd	76abc	71a
Pyroxasulfone + Thiencarbazone	238 + 5	56ab	74abc	72a
Thiencarbazone	5	64a	80a	79a
Pyroxasulfone + Pyroxulam	119 + 15	50bc	64cd	58bc
Pyroxasulfone + Pyroxulam	238 + 15	49bc	67bc	68ab
Pyroxulam	15	34f	49e	49c
Pyroxasulfone + Propoxycarbazone	119 + 10	41def	53de	51c
Pyroxasulfone + Propoxycarbazone	238 + 10	44cde	64cd	56bc
Propoxycarbazone	10	34f	41e	33d

[a] Letters in each column represent means separation with Fisher's F protected LSD at α=0.05.

Some supplemental control was achieved with various tank-mix combinations that included pyroxulam or propoxycarbazone. Two and 4-weeks after application, tank-mixed pyroxasulfone and pyroxulam provided greater foxtail control than individual applications of either herbicide. Propoxycarbazone tank-mixed with 238 g ai ha^{-1} pyroxasulfone increased green foxtail control compared to individual applications of pyroxasulfone and propoxycarbazone. However, pyroxasulfone, pyroxulam, and propoxycarbazone all provided poor green foxtail control, and the supplemental control observed was still inadequate, <70%.

Pyroxasulfone applied alone gave very little control of wild oat. The greatest control of wild oat was 20%, with 238 g ai ha^{-1} 4-weeks after application (Table 12). Two weeks after application, individual treatments of ALS-inhibiting herbicides provided similar control to the same herbicides tank-mixed with 119 and 238 g ai ha^{-1} of pyroxasulfone. Theincarbazone tank-mixed with 119 g ai ha^{-1} pyroxasuflone was the exception with less control of wild oat than individual applications of 5 g ai ha^{-1} theincarbazone.

Table 13. Pyroxasulfone as a tank mix with ALS inhibitors control of wild oat 2, 4 and 6 weeks after application.

		Rating (WAA)		
Treatment	Herbicide rate	2	4	6
	-g ai ha^{-1}-		——————g——————	
Pyroxasulfone	119	5e[a]	10f	5f
Pyroxasulfone	238	5e	20e	5f
Pyroxasulfone + Flucarbazone	119 + 22	70abc	97ab	96a
Pyroxasulfone + Flucarbazone	238 + 22	69abc	94abcd	98a
Flucarbazone	22	69abc	95ab	96ab
Pyroxasulfone + Thiencarbazone	119 + 5	65cd	97a	99a
Pyroxasulfone + Thiencarbazone	238 + 5	70abc	97a	99a
Thiencarbazone	5	74a	93bcd	99a
Pyroxasulfone + Pyroxulam	119 + 15	65cd	90d	86e
Pyroxasulfone + Pyroxulam	238 + 15	69abc	94abcd	95abc
Pyroxulam	15	69abc	91cd	90cde
Pyroxasulfone + Propoxycarbazone	119 + 10	63d	93bcd	91bcd
Pyroxasulfone + Propoxycarbazone	238 + 10	71ab	94abc	91bcd
Propoxycarbazone	10	66bcd	91cd	88de

[a] Letters in each column represent means separation with Fisher's F protected LSD at α=0.05.

Four weeks after application, theincarbazone applied alone at 5 g ai ha^{-1} had less wild oat control than when tank-mixed with 119 and 238 g ai ha^{-1} pyroxasulfone, at 93, 97, and 97% control, respectively. Individual applications of flucarbazone, pyroxsulam, and propoxycarbazone had similar control to tank-mixed combinations with 119 and 238 g ai ha^{-1} pyroxasulfone. Six weeks after application individual applications of flucarbazone, theincarbazone, pyroxsulam, and propoxycarbazone each provided similar control with or without the addition of 119 and 238 g ai ha^{-1} pyroxasulfone.

Wheat treated with 119 and 238 g ai ha^{-1} pyroxasulfone had similar yield to untreated check plots (Table 13). The addition of pyroxasulfone to a tank-mix with flucarbazone, theincarbazone, pyroxulam, or propoxycarbazone did not increase yield.

Table 14. Pyroxasulfone as a tank-mix with ALS inhibitors yield.

Treatment	Herbicide rate	Yield
	-g ai ha^{-1}-	-g-
Untreated	-	1818c[a]
Pyroxasulfone	119	1800c
Pyroxasulfone	238	1819c
Pyroxasulfone + Flucarbazone	119 + 22	2453ab
Pyroxasulfone + Flucarbazone	238 + 22	2543ab
Flucarbazone	22	2534ab
Pyroxasulfone + Thiencarbazone	119 + 5	2490ab
Pyroxasulfone + Thiencarbazone	238 + 5	2641a
Thiencarbazone	5	2366ab
Pyroxasulfone + Pyroxulam	119 + 15	2290b
Pyroxasulfone + Pyroxulam	238 + 15	2422ab
Pyroxulam	15	2416ab
Pyroxasulfone + Propoxycarbazone	119 + 10	2359ab
Pyroxasulfone + Propoxycarbazone	238 + 10	2337b
Propoxycarbazone	10	2306b

[a] Letters in each column represent means separation with Fisher's F protected LSD at α=0.05.

Lower green foxtail and wild oat control was observed in the field compared to greenhouse results. Conflicting results could be due to insufficient precipitation in the 2016 growing season. As previously stated, surface applied herbicides generally require 1.27 to 2.54 cm of precipitation within 7-10 days of the application (Hager and Sprague 2001), and the pyroxasulfone herbicide label requires 1.27 cm for weed control (Zidua product label 2015). Pyroxasulfone targets seedling shoot growth (Szmigielski et al. 2013), and to be effective must be moved by rainfall or irrigation into the seedling zone. In 2016 there wasn't a significant rainfall event in the two weeks that followed the herbicide applications (Table 14). Total rainfall over the two weeks did cumulate over 1.27 cm at both Fargo and Prosper. However, pyroxasulfone has a low solubility of 3.49 mg L^{-1}, and with a series of low rainfall events it is possible pyroxasulfone was unable to desorb into solution.

Table 15. Two weeks of daily rainfall following treatments in 2016 field experiments.

DAA[a]	Fargo	Prosper
	----------cm----------	
1	0[b]	0
2	0.81	0
3	0.18	0
4	0	0.41
5	0.43	0
6	0	0.05
7	0	0
8	0	1.10
9	0.41	0.03
10	0	0
11	0	0.10
12	0	0.51
13	0.53	0
14	0.06	0
Total	2.42	2.20

[a] DAA, days after application.
[b] cm

Foliar vs. Soil Activity

Green foxtail, wild oat, and downy brome had similar treatment responses when different plant tissue was exposed to pyroxasulfone (Table 15). Treatments applied only to foliage provided little to no control, regardless of species. The highest observed control from a foliar application was 10% downy brome control. However, damage observed in pots with foliar applied treatments were wilted plants, and resembled drought stress more than herbicide damage. This could have been due to a microenvironment effect created by the black activated charcoal. The charcoal could have increased the temperature enough to damage the cool season grasses. Greenhouse temperatures were warmer at the beginning of the experiment and cooled down towards the end. This could explain why plants with foliar treatments were able to grow out of this stress as the experiment progressed.

Table 16. Foliar, soil, and combined foliar and soil pyroxasulfone application effects on grass control.

Treatment		Species		
		Green foxtail[b]	Wild oat	Downy brome
	-g ai ha^{-1}-		%	
			2 WAA[a]	
Foliar	119	4c	9c	0b
	238	5c	8c	10b
Foliar & Soil	119	70b	52b	63a
	238	71b	53b	66a
Soil	119	71b	54b	56a
	238	73a	59a	67a
			4 WAA	
Foliar	119	3d	2e	0d
	238	3d	1e	1d
Foliar & Soil	119	80c	66d	78c
	238	83b	69c	83b
Soil	119	86ab	73b	85ab
	238	87a	77a	86a

[a] WAA, weeks after application; were treated as separate experiments.
[b] Species separation were run independently.
[c] Letters in each column represent means separation with Fisher's F protected LSD at α=0.05.

Across both evaluation timings, soil alone applications of 238 g ai ha^{-1} had the highest control of all species tested. Two weeks after application, soil alone and combined foliar and soil treatments had similar downy brome control. Four weeks after application both soil applied treatments provided similar green foxtail and downy brome control.

All soil alone and combined foliar and soil treatments provided similar wild oat and downy brome biomass reduction. Pyroxasulfone at 238 g ai ha^{-1}, applied to the soil, had greater green foxtail biomass reduction than the 119 g ai ha^{-1} foliar and soil applied treatment. Foliar alone treatments to downy brome had more biomass than the untreated check. More green foxtail biomass was collected from pots where foliage was treated with 119 g ai ha^{-1}

pyroxasulfone than from plants that weren't treated, but there was no difference in green foxtail biomass from the untreated check and 238 g ai ha^{-1} pyroxasulfone treatment. The reason foliar treated plants had more biomass than untreated plants could also have been due to the microenvironment created by the charcoal. As the temperatures in the greenhouse changed from hot to cold the warmer microenvironment could have shifted from being detrimental to beneficial.

Table 17. Foliar, soil, and combined foliar and soil pyroxasulfone application effects on grass biomass.

Treatment		Species		
		Green foxtail[a]	Wild oat	Downy brome
	-g ai ha^{-1}-	g		
Untreated				
	0	1.24b[b]	2.03a	1.16b
Foliar				
	119	1.40a	2.26a	1.38a
	238	1.27ab	2.25a	1.33a
Foliar & Soil				
	119	0.40c	0.47b	0.19c
	238	0.32cd	0.47b	0.16c
Soil				
	119	0.27cd	0.31b	0.10c
	238	0.23d	0.29b	0.12c

[a] Species separation were run independently.
[b] Letters in each column represent means separation with Fisher's F protected LSD at α=0.05.

Weed control with pyroxasulfone was almost exclusively due to root uptake. All treatments applied to foliage resulted in ≤3% control 4-weeks after application. Plants with pyroxasulfone foliar applied had more dry biomass than control pots. Again, this is likely due to a warmer microenvironment caused by the layer of activated charcoal, but still confirms pyroxasulfone had little to no activity when foliar applied. These results agree with Yamaji et al. (2016), where results indicated pyroxasulfone is very effective when in contact with the roots.

Weed control by preemergence herbicides are affected by various environmental factors such as soil properties, rainfall, and physicochemical properties (Yamaji et al. 2016), which all varied from the field to the greenhouse. The first factor that could have contributed to higher control observed in the greenhouse was the difference in soil type. Pyroxasulfone is more mobile in coarse textured soils than in fine and medium textured soils (Shaner et al. 2014). Experiments conducted in the field were subject to either a loam or a silty clay loam, and greenhouse work was conducted with a sandy loam. This likely contributed to the increased weed control observed in the greenhouse. These results would also agree with those found by Yamaji et al. (2016) where twice as much pyroxasulfone was required in clay soils, compared to sandy soils, to inhibit >85% plant growth.

The second factor that could have caused varying results was the difference in soil moisture and precipitation. Preemergence herbicides require precipitation for availability or movement into the soil, and reduced weed control can result from dry conditions (Sewart et al. 2010). The 2015 (Table 18) and 2016 growing seasons in Fargo and Prosper North Dakota were dry, and the lack of a significant rainfall after herbicide application most likely prevented pyroxasulfone from becoming available to the plant. Greenhouse pots were watered daily to prevent soil moisture from becoming the limiting factor. The controlled moisture present in the greenhouse could be a reason for the control observed.   Similar research experiments conducted in the greenhouse achieved 100% weed control (Szmigielski et al. 2013; Yamaji et al. 2014, 2016). Less control observed in this work, compared with other authors, is most likely due to application timing. In all previous studies pyroxasulfone was used preemergence, and it is likely more pyroxasulfone is required to achieve the same levels of control when applied postemergence.

Table 18. Two weeks of daily rainfall following treatments on 2015 field experiments.

	Fargo 1.1[b]	Fargo 1.2	Fargo 1.3	Fargo 2.1	Fargo 2.2	Fargo 2.3	Fargo 3.1	Fargo 3.2	Fargo 3.3	Prosper 1.1	Prosper 1.2	Prosper 1.3
DAA[a]	-----	-----	-----	-----	-----	-----	mm	-----	-----	-----	-----	-----
1	0	0	0	37.3	0	0.3	37.3	11.9	0	0	0	0
2	0	11.9	0	9.7	0	1.5	9.7	0	0	0	0	0
3	0	0	0	0	0	3.3	0	0.3	0	0	10.2	0
4	0	0.3	0	0	0	7.1	0	0.3	0	7.6	0	0
5	0	0.3	24.1	0.3	24.1	0	0.3	0	24.1	0	0.3	40.4
6	8.6	0	0	0.3	0	5.8	0.3	0	0	0.3	0	0
7	0	0	6.9	0	6.9	0.3	0	0	6.9	11.2	0	7.4
8	0	0	0	0	0	0	0	0	0	0.3	0	0
9	37.3	0	0	12.0	0	1.3	12.0	0	0	0	0	0.3
10	9.7	0	0.3	0	0.3	0	0	24.1	0.3	0	0	1.27
11	0	24.1	1.5	0.3	1.5	0	0.3	0	1.5	0	40.4	1.8
12	0	0	3.3	0.3	3.3	0	0.3	6.9	3.3	0	0	14.0
13	0.3	6.9	7.1	0	7.1	0	0	0	7.1	0	0.3	3.8
14	0.3	0	0	0	0	0	0	0	0	0	0	0
Total	56.2	43.5	43.2	60.2	43.2	19.8	19.4	43.5	43.2	19.4	51.2	69.0

[a] DAA, days after application

[b] Different application timings within the same experiment

Another factor that can affect the efficacy of preemergence herbicides is soil organic matter. Research results on the influence of OM on pyroxasulfone vary. Szmigielski et al. (2013) found increased pyroxasulfone adsorption to organic matter decreased pyroxasulfone bioactivity, which could lead to decreased weed control. However, an experiment by Yamaji et al. (2016) found no correlation between OM and ED_{90}, while Knezevic et al. (2009) found 301, 283, and 413 g ai/ha were required to achieve ED_{90} for soils with 1, 2 and 3% OM. Generally, soils with higher OM are more likely to adsorb the chemical more readily than soils with lower OM. Odero & Wright (2012) found pyroxasulfone can provide excellent weed control in high OM soils at the labeled use rate, but the ED_{90} varied depending on weed species.

Results on weed control with pyroxasulfone varied with each experiment. Differences in herbicide response amongst past experiments most likely indicates effective rates of pyroxasulfone will be dictated by soil moisture, rainfall, soil type, OM content, and plant species. With field studies subject to fine soils, ≥ 3.5% OM, and inadequate precipitation, the environmental factors were in favor of poor weed control. This and applying pyroxasulfone as a postemergence is likely why zero to no control was observed on broadleaf weeds, and only suppression of green foxtail. The reason for green foxtail suppression in poor conditions was likely due to its level of susceptibility. Tidemann et al. (2014) found the ED_{50} for green foxtail ranged from 0.02 to 0.26 g ai ha^{-1} of pyroxasulfone, which is less than 1/1000 of the dose used in field experiments. With green foxtails high level of susceptibility, and only suppression observed in the field, it is possible very little pyroxasulfone made it into the plant.

Greenhouse studies demonstrated a broad spectrum of grass species can be controlled postemergence with pyroxasulfone, and that entirely all the activity was from root uptake. Poor control observed in the field, at the same application timing and rates, demonstrated strong environmental influences. Pyroxasulfone’s selectivity and mode of action makes it an enticing product. However, to be a viable option more information on pyroxasulfone’s interaction with soil type and OM content at different soil saturation levels should be tested across susceptible, moderately susceptible, and tolerant species. Early to preemergence applications of pyroxasulfone are more viable than postemergence applications, as lower weed control was observed in these studies compared to past research.

REFERENCES

Anonymous (2015) Plant and Soil Sciences eLibrary, Herbicide Inhibitors of VLCFA Elongation. http://passel.unl.edu/pages/informationmodule.php?idinformationmodule=1130447055&topicorder=5&maxto=6. Accessed: October 13, 2015

Anonymous (2015) Zidua® herbicide product label. BASF Publication No. NVA 2015-04-388-0072. Research Triangle Park, NC: BASF. 17 p

Busi R, Gaines T, Vila-Aiub M, Powles S (2014) Inheritance of evolved resistance to a novel herbicide (pyroxasulfone). Plant Science 217-218:127-134

College of Agriculture and Life Sciences, Cornell University (2015) Cornell University, Factors Affecting Soil-Applied Herbicides | Field Crops. https://fieldcrops.cals.cornell.edu/corn/weed-control-corn/factors-affecting-soil-applied-herbicides. Accessed: November 23, 2015

Crop Protection USA (2015) BASF, Zidua Herbicide. http://agproducts.basf.us/products/zidua-herbicide.html Accessed: October 13, 2015

Curran W, Lingenfelter D (2013) Pyroxasulfone: The New Kid in the Neighborhood. Penn State College of Agricultural Sciences. http://extension.psu.edu/plants/crops/news/2013/04/pyroxasulfone-the-new-kid-in-the-neighborhood Accessed: October 13, 2015

Gunsolus JL (2013) University of Minnesota Extension Agriculture, Herbicide Resistant Weeds. http://www.extension.umn.edu/agriculture/crops/weed-management/herbicide-resistant-weeds/ Accessed: October 4, 2015

Hager A, Sprague C (2001) Dry Soils and Soil-Applied Herbicides. University of Illinois Extension. Available at http://www.ipm.uiuc.edu/bulletin/pastpest/articles/200106i.html Accessed: November 23, 2015

Hartzler B (2002) Absorption of Soil-Applied Herbicides. Iowa State University Weed Science. Available at http://www.weeds.iastate.edu/mgmt/2002/soilabsorption.htm Accessed: November 23, 2015

Heap I (2015) The International Survey of Herbicide Resistant Weeds. www.weedscience.org Accessed: October 4, 2015

Hunt RL (2010) Pyroxasulfone Tolerance of Navy and Pinto Beans. M.S. Thesis. Fargo, ND: North Dakota State University

Knezevic S, Datta A, Scott J, Porpiglia P (2009) Dose-Response Curves of Kih-485 for Preemergence Weed Control in Corn. Weed Technology 23:34-39

Mueller T, Steckel L (2011) Efficacy and Dissipation of Pyroxasulfone and Three Chloracetamides in a Tennessee Field Soil. Weed Science 59:574-579

North Dakota Agricultural Weather Network. 2017. Available at https://ndawn.ndsu.nodak.edu/ weather-data-daily.html (accessed 19 Oct. 2017) Fargo, ND

Mergoum M, Frohberg R, Stack R, Simsek S, Adhikari T, Rasmussen J, Zhong S, Acevedo M, Alamri M, Singh P, Friesen T, Anderson J (2012) ‘Prosper’: A High-Yielding Hard Red Spring Wheat Cultivar Adapted to the North Central Plains of the USA. Crop Science Society of America. 7:75-80

Odero D, Wright A (2012) Response of Sweet Corn to Pyroxasulfone in High-Organic-Matter Soils. Weed Technology 27:341-346

Satchivi N, DeBoer G, Bell J (2017) Understanding the Differential Response of *Setaria virdis L*. (green foxtail) and *Setaria pumila Poir*. (yellow foxtail to Pyroxsulam. J. Agric. Food Chem 65:7328-7336

Shaner D.L., Jachetta J, Senseman S, Burke I, Hanson B, Jugulam M, Tan S, Reynolds J, Strek H, McAllister R, Green J, Glenn B, Turner P, Pawlak J (2014) Herbicide Handbook. 10th edn. Lawrence, KS: Weed Science Society of America. Pp 395-396

Stewart C, Nurse R, Hamill A, Sikkema P (2010) Environment and Soil Conditions Influence Pre- and Postemergence Herbicide Efficacy in Soybean. Weed Technology 24:234-243

Szmigielski A, Johnson E, Schoenau J (2013) A Bioassay Evaluation of Pyroxasulfone Behavior in Prairie Soils. Pesticide Science 39:22-28

Tanetani Y, Ikeda M, Kaku K, Shimizu T, Matsumoto H (2013) Role of Metabolism in the Selectivity of a Herbicide, Pyroxasulfone, Between Wheat and Rigid Ryegrass Seedlings. Pesticide Science 38:152-156

Tidemann B, Hall L, Johnson E, Beckie H, Sapsford K, Willenborg C, Raatz L (2014) Additive Efficacy of Soil-Applied Pyroxasulfone and Sulfentrazone Combinations. Canadian Journal of Plant Science. 94:1245-1253

Tranel P, Wright R (2002) Resistance of Weeds to ALS-Inhibiting herbicides: What have we Learned? Weed Science 50:700-712

USDA-Natural Resources Conservation Service. 2016. Available at http://websoilsurvey.nrcs. usda.gov/ app/HomePage.htm (accessed 19 Oct. 2017). USDA-NRCE, Washington, DC

Walsh M, Fowler T, Crowe B, Ambes T, Powles S (2011) The Potential for Pyroxasulfone to Selectively Control Resistant and Susceptible Rigid Ryegrass (Lolium rigidum) Biotypes in Australian Grain Crop Production Systems. Weed Technology 25:30-37

Yamaji Y, Honda H, Kobayashi M, Hanai R, Inoue J (2014) Weed Control Efficacy of a Novel Herbicide, Pyroxasulfone. Pesticide Science 39:165-169

Yamaji Y, Honda H, Hanai R, Inoue J (2015) Soil and Environmental Factors Affecting the Efficacy of Pyroxasulfone for Weed Control. Pesticide Science 41:1-5

Yamaji Y, Honda H, Hanai R, Inoue J (2016) Soil and Environmental Factors Affecting the Efficacy of Pyroxasulfone for Weed Control. Pesticide Science 41:1-5

Zollinger R, Ries L, Hammond J (2003) Survey of weeds in North Dakota-2000. Extension Report 83; Extension Services, North Dakota State University: Fargo, ND, 2003; Pp 9, Table 2

Zollinger R, Ries J (2007) Sunflower Tolerance to KIH-485. National Sunflower Association. 2008 Research Proceedings. Available at http://www.sunflowernsa.com Accessed: November 16, 2015

Zollinger R, Christoffers M, Dalley C, Endres G, Gramig G, Howatt K, Jenks B, Lym R, Ostlie M, Peters T, Robinson A, Thostenson A, Valenti H (2015) 2015 North Dakota Weed Control Guide. NDSU Ext. Service. W-2