Original Article

A bioassay evaluation of pyroxasulfone behavior in prairie soils

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Pyroxasulfone behavior in prairie soils was evaluated using a 7-day sugar beet (*Beta vulgaris* L.) shoot length inhibition bioassay. Pyroxasulfone bioactivity in soil, assessed from 0 to 184 g a.i./kg, was primarily related to organic carbon content ($p=0.001$) with decreased bioactivity occurring in soils of high organic carbon. Pyroxasulfone bioactivity, measured after soil pH adjustments, was reduced as soil pH decreased demonstrating that at low soil pH pyroxasulfone becomes less available to plants. Pyroxasulfone half-lives estimated for dissipation at 25°C and moisture content of 85% field capacity ranged from 16 to 69 days. Organic carbon content ($p=0.034$) and soil pH ($p=0.008$) were significant in affecting pyroxasulfone half-lives with faster dissipation occurring in soils of high organic carbon content and high pH. Interactions between soil-incorporated pyroxasulfone and sulfentrazone were either antagonistic or additive and the nature of these interactions could vary with soil type. © Pesticide Science Society of Japan

Keywords: pyroxasulfone, bioassay, bioactivity, dissipation, pH, interactions.

Introduction

Pyroxasulfone is a novel pre-emergence herbicide that is efficacious against annual grasses and small-seeded broadleaf weeds, and is used primarily for weed control in corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), soybean (*Glycine max* L.), and other crops such as sunflower (*Helianthus annuus* L.).^{1–6} Pyroxasulfone is classified as Group 15 herbicide by the Weed Science Society of America and as Group K3 herbicide by the Herbicide Resistance Action Committee. Pyroxasulfone is considered to be a seedling shoot growth inhibitor and the primary target enzyme is very long chain fatty acid elongase. It inhibits several fatty acid elongation steps for shoot formation and cell proliferation in the plants.⁷

Pyroxasulfone (3-[(5-(difluoromethoxy)-1-methyl-3-(trifluoromethyl)pyrazol-4-yl)methylsulfonyl]-4,5-dihydro-5,5-dimethyl-1,2-oxazole) (Fig. 1) has the following selected physical properties: water solubility at 20°C = 3.49 mg/L, $\log K_{OW} = 2.39$, Henry's law constant at 20°C = 2.65×10^{-9} atm m³/mol. Pyroxasulfone molecule does not ionize as it does not have a dissociable moiety (Fig. 1).^{5,8}

Typically, recommended pyroxasulfone field application rates depend on soil texture and organic matter content, and are higher in soils of high clay and high organic matter content.^{1,4,5,8–10} In Ontario (Canada) where pyroxasulfone is registered for weed

control in corn, the field application rates are 123 g a.i./ha on coarse (sandy) soil, 166 and 208 g a.i./ha on medium to medium-fine soil with organic matter content $\leq 3\%$ and $>3\%$, respectively, and 247 g a.i./ha on fine-textured (high clay content) soil.⁸ Pyroxasulfone may not provide complete control of some weeds and may require use of sequential herbicide applications or use of tank mixtures or premixed formulations with other herbicides such as atrazine,^{2,8,11} glyphosate,^{8,12} flumioxazin,⁵ fluthiacet-methyl,⁹ or atrazine plus fluthiacet-methyl.¹⁰ Moisture is necessary to activate pyroxasulfone in soil and dry weather following application may reduce effectiveness. However, when adequate moisture is received after dry conditions, pyroxasulfone will control susceptible germinating weeds.⁹ Pyroxasulfone has residual properties and enables control of weeds emerging later in the season. The reported dissipation half-lives are in the range from 4 to 35 days,⁸ however, because pyroxasulfone may persist in soil to the next growing season, herbicides containing pyroxasulfone alone and premixed formulations containing pyroxasulfone have 18-month rotation restriction to all crops except corn, soybean and wheat.^{8,9}

Because pyroxasulfone mode of action is distinctly differ-

Fig. 1. Chemical structure of pyroxasulfone.

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ent from the mode of action of many commonly used herbicides such as triazines, sulfonylureas and imidazolinones to which weeds developed resistance, it provides a new alternative in combating the weed resistance problems.⁵⁾ By using pyroxasulfone in rotation^{4,12)} or in combination with other herbicides^{2,6,11–13)} the efficacy of weed control is improved and the likelihood of weeds developing resistance may be decreased or delayed.

Crop tolerance trials conducted in western Canada have indicated that spring wheat, winter wheat, and field pea (*Pisum sativum* L.) exhibit acceptable tolerance to pyroxasulfone, while weed control efficacy trials have shown consistent control of *Bromus* spp. and suppression to control of *Galium* spp. and wild oat (*Avena fatua* L.).¹⁴⁾ Since pyroxasulfone will become available in western Canada for use in wheat production in the near future, the evaluation of pyroxasulfone behavior in Canadian prairie soils with a suitable bioassay is needed. Plant bioassays are a useful tool in research and in soil testing because they detect the actual bioavailable amount of herbicide in soil, while chemical techniques are suitable for determination of total herbicide present in soil. Despite some disadvantages, such as lack of specificity and variability in response with plant species and soil type, bioassays are generally very sensitive and detect amounts of herbicides available to sensitive plants at low concentrations. Because pyroxasulfone is a relatively new herbicide, no bioassay technique has been proposed for the detection of its residues in soil. The objectives of this study were (1) to develop a plant bioassay for detection of pyroxasulfone in soil, (2) to investigate pyroxasulfone bioactivity in soil, (3) to evaluate the effect of soil pH on pyroxasulfone bioactivity, (4) to assess pyroxasulfone dissipation in soil, and (5) to examine pyroxasulfone interactions with sulfentrazone.

Materials and Methods

1. Soils

Five soils typical of the Canadian prairies were collected in Saskatchewan from the 0 to 10 cm depth, air-dried at room temperature and passed through a 2-mm sieve. Selected soil properties are listed in Table 1. Soil organic carbon was determined using a Leco CR-12 Automated Combustion Carbon Determinator at 840°C (Leco Corporation, St. Joseph, MI). Soil textures were assessed using a Horiba Laser Scattering Particle Size Distribution Analyzer (Horiba Instruments, Irvine, CA). Soil pH was mea-

sured in a 1:2 soil:water suspensions, and field-capacity water content was estimated by determining the volume of water required to completely wet the air-dried soil to the bottom of a plastic vial.

2. Chemicals

A commercial formulation KIH-485 (FMC Corporation-Innovation Center, Ewing, NJ) that contains 85% pyroxasulfone was used for solution preparation. Assuming that applied pyroxasulfone remains in the top 10 cm of soil and a soil bulk density of 1.3 g/cm³, a field application rate of 120 g a.i./ha was determined to be equivalent to 92 µg a.i./kg dry soil. Pyroxasulfone stock solution was prepared by dissolving 0.108 g KIH-485 in 1 L of water:acetone mixture (4:1 by volume) yielding a pyroxasulfone concentration of 92 mg a.i./L. Through further dilutions with water, a series of solutions containing pyroxasulfone at concentration of 0, 2.3, 4.6, 6.9, 9.2, 13.8 and 18.4 mg a.i./L was prepared. A 0.5-mL volume of each pyroxasulfone solution was combined with the volume of distilled water equivalent to 100% moisture content at field capacity and was added to 50 g of air-dried soil, yielding a pyroxasulfone concentration in the soil of 0, 23, 46, 69, 92, 138 and 184 µg a.i./kg.

3. Bioassay conditions

After adding pyroxasulfone and water to the soil, soil was hand-mixed and transferred to 2-oz WhirlPak[®] bag (VWR International, Mississauga, ON, Canada). Soil in the bag was gently packed to form a layer approximately 8 cm high, 6 cm long and 1 cm wide. Six seeds of the desired bioassay plant species were planted at a 2-mm depth and the soil surface was covered with a 5-mm layer of plastic beads to reduce soil drying.¹⁵⁾ Plants were grown in the laboratory under fluorescent lights that had photosynthetic photon flux density of 16 µmol/m²/s at the plant level, and plants were watered daily to 100% field capacity by adding water to a predetermined weight. At harvest time, intact plants were recovered from soil after the WhirlPak[®] bag was opened and soil was washed away with water. Shoot and root lengths were measured with a ruler and percent shoot or root length inhibition was calculated using the formula¹⁶⁾:

$$\text{Inhibition (\%)} = 100 - \% \text{ of control} = (1 - L_t/L_0) \times 100\% \quad (1)$$

where L_t is the shoot or root length measured in the herbicide-treated soil and L_0 is the shoot or root length in the untreated

Table 1. Selected characteristics of soils used in this study

Soil (location)	Soil series	OC ^{a)} (%)	pH ^{b)}	Sand ^{c)} (%)	Clay ^{c)} (%)	FC ^{d)} (%)
Central Butte (1)	Haverhill loam	1.3	7.9	52	23	14
Scott (1)	Scott loam	2.0	5.0	43	19	18
Central Butte (2)	Haverhill clay loam	2.2	7.2	28	38	18
Saskatoon	Sutherland clay	3.2	7.8	14	60	28
Scott (2)	Weyburn loam	3.2	6.2	35	22	22

^{a)} OC, organic carbon content. ^{b)} pH measured in a 1:2 soil:H₂O suspension. ^{c)} Textural classes are defined in size distribution as clay <0.002 mm, silt 0.002–0.05 mm, sand >0.05 mm, according to Canadian System of Soil Classification 3rd edition. ^{d)} FC, moisture content at field capacity.

soil.

4. Plant selection for the bioassay

To identify a suitable plant species and a plant parameter for the detection of pyroxasulfone in soil, shoot and root reduction of sugar beet (*Beta vulgaris* L. 'Beta 1385'), canola (*Brassica napus* L. 'Invigor' 5770) and oriental mustard (*Brassica juncea* L. 'Cutlass') were measured in response to soil-incorporated pyroxasulfone at 92 µg a.i./kg, and were compared to shoot and root length obtained in the untreated soil after 4 days of growth in the Haverhill loam soil (Table 1).

To enhance plant response to pyroxasulfone, sugar beet was then grown for increasing number of days up to 8 days in the pyroxasulfone-treated soil at 92 µg a.i./kg, and in the untreated soil, and percent shoot and root inhibition was determined for each growth period.

5. Pyroxasulfone bioactivity in soil

To examine pyroxasulfone bioactivity in soil, five soils of varying properties were used (Table 1). Pyroxasulfone was added to soil in the range from 0 to 184 µg a.i./kg (approximately equivalent to a field application rate from 0 to 240 g a.i./ha) and the 7-day sugar beet shoot length bioassay was applied. Dose-response curves were obtained by graphing shoot length inhibition data vs. pyroxasulfone concentration using the log-logistic model¹⁷⁾:

$$\% \text{ of control} = C + (D - C) / (1 + [x / GR_{50}]^b) \quad (2)$$

where C=lower limit of the curve, D=upper limit of the curve, b=slope of the curve around GR₅₀ value, and GR₅₀=concentration corresponding to 50% inhibition. Pyroxasulfone concentration required for 50% shoot length inhibition (GR₅₀ value) was determined from the dose-response curves for each soil.

6. Modification of soil pH

To assess the effect of soil pH on pyroxasulfone bioactivity, soil pH was altered to produce values either above or below natural pH values. In Haverhill clay loam and Scott loam (Table 1), soil pH was increased by adding a suspension of 0.2 g CaCO₃ per 50 g soil in a volume of water equivalent to 100% field capacity, and soil pH was lowered using 0.5 mL of 1 M HCl solution per 50 g soil added to soil with a volume of water equivalent to 100% field capacity. In Haverhill loam (Table 1), the addition of CaCO₃ did not raise soil pH, as this soil was calcareous to begin with, and to produce a range of soil pH values, the pH in this soil was lowered using 0.5 mL and 1 mL of 1 M HCl solution per 50 g of soil. After acid or base addition, soils in plastic containers were hand-mixed, covered, and allowed to equilibrate for 1 week. Soils were then air-dried, sieved (2 mm), and pH was determined. Soils with altered pH were then supplemented with pyroxasulfone in the range from 0 to 184 µg a.i./kg and shoot length of sugar beet was measured in response to pyroxasulfone after 7 days of growth. Dose-response curves were obtained for each soil pH using Eq. 2.

7. Pyroxasulfone dissipation under laboratory conditions

For the dissipation study, soils were prepared by adding pyroxasulfone at 92 µg a.i./kg to Haverhill loam, Scott loam and Haverhill clay loam, and at 138 µg a.i./kg to Sutherland clay and Weyburn loam (Table 1). A 0.5-mL volume of either 0.092 or 0.138 mg a.i./L pyroxasulfone standard solution and a volume of water equivalent to 85% field capacity were added to 50-g soil portions in Styrofoam cups. Soils were hand-mixed, cups were capped with lids and placed in an incubator set at 25°C. Soils were watered every other day to predetermined weight to bring soil moisture content back to 85% field capacity. Soils were sampled every two weeks up to 16 weeks after treatment. At each sampling, soils were air-dried, sieved, and residual pyroxasulfone was determined by the 7-day sugar beet shoot bioassay. Pyroxasulfone half-life (T_{1/2}) in each soil was estimated from the dissipation curves after fitting the data to a first order decay model¹⁸⁾:

$$C = C_0 e^{-kT} \quad (3)$$

where C=herbicide concentration remaining in soil after time T, C₀=initial herbicide concentration, k=dissipation rate constant.

8. Pyroxasulfone and sulfentrazone interactions

To examine interactions between soil-incorporated pyroxasulfone and sulfentrazone, the combined effect of these two herbicides on sugar beet shoot length inhibition was evaluated in Haverhill loam and Haverhill clay loam soils (Table 1). Soils were supplemented with combinations of pyroxasulfone in the range from 0 to 184 µg a.i./kg with sulfentrazone added at 25 and at 50 µg a.i./kg level in Haverhill loam and in Haverhill clay loam, respectively. These quantities of added sulfentrazone were approximately equal to the sulfentrazone GR₅₀ values obtained from the sulfentrazone dose-response curves for these two soils.¹⁹⁾ Observed shoot length inhibition was determined using shoot length of sugar beet that was measured in response to combinations of pyroxasulfone and sulfentrazone. Expected shoot length inhibition was calculated using Colby's formula²⁰⁾:

$$E = X + Y - XY/100 \quad (4)$$

where X is the plant growth inhibition (%) due to compound A, and Y is the plant inhibition due to compound B. Dose-response curves were constructed for the observed and expected shoot length inhibition using Eq. 2, and the observed and expected inhibition values for each combination of pyroxasulfone and sulfentrazone were compared by a *t*-test in order to determine the nature of the interaction between these two herbicides. Herbicide interactions may be synergistic, antagonistic or additive depending on whether the combined effect on the target plant is greater, less than or equal to the summed effect of the herbicides applied alone.^{20,21)}

All experiments were replicated four times and repeated as two independent runs. The data from two runs in each experiment were combined. Dose-response curves (Eq. 2) from which GR₅₀ values were estimated and dissipation curves (Eq. 3) from

which half-lives were determined were obtained after fitting the data to nonlinear regressions using Sigma Plot (Sigma Plot, San Rafael, CA). Multiple regression analysis of GR_{50} values and dissipation half-lives vs. organic carbon content (%), soil pH and clay content (%) was performed using Excel (Microsoft Corporation, Redmond, WA).

Fig. 2. Shoot and root length inhibition of sugar beet grown from 4 to 8 days in response to 92 µg a.i./kg pyroxasulfone in the Haverhill loam soil (each data point represents mean ± standard deviation; bars with the same letters are not different at 0.05 significance level).

Results and Discussion

1. Development of a laboratory bioassay

After 4 days of growth, sugar beet, canola and oriental mustard showed a relatively small and comparable inhibition due to added pyroxasulfone at 92 µg a.i./kg. The percent inhibition (mean ± S.D.) of shoot length was 24.5 ± 5.2, 25.8 ± 9.9 and 24.0 ± 12.2, and of root length was 19.6 ± 7.0, 18.9 ± 9.8 and 22.8 ± 14.2 for sugar beet, canola and oriental mustard, respec-

Fig. 3. Pyroxasulfone dose-response curves in prairie soils determined by the 7-day sugar beet shoot length bioassay; each data point represents mean ± standard error; estimated equations are listed in Table 2.

Table 2. Estimated equations for pyroxasulfone dose-response curves obtained by fitting the data from the 7-day sugar beet shoot length bioassay to Eq. 2

Soil	Equation	R ²
Figure 3		
Haverhill loam	$y = 26.8 + 73.2 / (1 + [x/32.5]^{1.1})$	0.966
Scott loam	$y = 30.0 + 66.2 / (1 + [x/90.7]^{2.4})$	0.946
Haverhill clay loam	$y = 29.8 + 67.3 / (1 + [x/88.6]^{1.9})$	0.937
Sutherland clay	$y = 30.0 + 69.1 / (1 + [x/100.8]^{2.0})$	0.952
Weyburn loam	$y = 30.3 + 66.5 / (1 + [x/130.0]^{2.7})$	0.972
Figure 4		
Haverhill loam pH 7.9 (natural)	$y = 26.8 + 73.2 / (1 + [x/32.5]^{1.1})$	0.966
pH 7.6	$y = 25.1 + 78.9 / (1 + [x/62.2]^{0.9})$	0.902
pH 7.4	$y = 27.0 + 66.6 / (1 + [x/103.5]^{0.9})$	0.853
Haverhill clay loam pH 7.4	$y = 29.5 + 69.1 / (1 + [x/63.8]^{1.6})$	0.973
pH 7.2 (natural)	$y = 29.8 + 67.3 / (1 + [x/88.6]^{1.9})$	0.937
pH 4.8	$y = 30.0 + 66.1 / (1 + [x/137.4]^{2.3})$	0.937
Scott loam pH 6.4	$y = 24.1 + 75.6 / (1 + [x/98.9]^{1.5})$	0.979
pH 5.0 (natural)	$y = 30.0 + 66.2 / (1 + [x/90.7]^{2.4})$	0.946
pH 4.3	$y = 49.9 + 49.1 / (1 + [x/237.5]^{1.3})$	0.861
Figure 5		
Haverhill loam (expected)	$y = 17.9 + 48.1 / (1 + [x/32.6]^{1.1})$	0.967
(observed)	$y = 18.0 + 47.4 / (1 + [x/102.7]^{1.0})$	0.920
Haverhill clay loam (expected)	$y = 30.0 + 34.4 / (1 + [x/73.9]^{3.1})$	0.915
(observed)	$y = 38.4 + 27.0 / (1 + [x/82.5]^{6.1})$	0.985

Table 3. Multiple regression analysis for pyroxasulfone GR₅₀ values (concentrations corresponding to 50% inhibition of sugar beet length) and selected soil characteristics

Model	Coefficient ^{a)}	Standard error	p value ^{b)}
Constant	63.6	50.5	0.234
Organic carbon (%)	38.8	8.7	0.001
Soil pH	-9.3	7.1	0.218
Clay (%)	-0.2	0.5	0.759

^{a)} Equation $y = 63.6 + 38.8 \times \text{OC} (\%) - 9.3 \times \text{soil pH} - 0.2 \times \text{clay} (\%)$; $R^2 = 0.806$; $F = 15.227$. ^{b)} Significance.

tively. Because sugar beet inhibition was more reproducible than that of canola and oriental mustard as evidenced by the smallest standard deviation, sugar beet was selected for further testing to enhance plant response to pyroxasulfone.

Shoot length inhibition of sugar beet grown for up to 8 days in response to 92 µg a.i./kg pyroxasulfone was higher than root length inhibition at each growth period (Fig. 2). Shoot length inhibition increased up to 7 days, and growing plants longer than 7 days did not significantly improve shoot length inhibition detection. Therefore, measuring shoot length inhibition of sugar beet after 7 days was selected for the use in a laboratory bioassay for determination of pyroxasulfone in soil.

2. Pyroxasulfone bioactivity in soil

Pyroxasulfone bioactivity evaluated by the 7-day sugar beet shoot length inhibition bioassay varied among the investigated soils (Fig. 3). The GR₅₀ values that were estimated from the dose-response curves ranged from 32.5 to 130 µg/kg (Table 2) with higher GR₅₀ values indicating decreased bioactivity of the herbicide in soil. Multiple regression analysis using organic carbon content (%), soil pH and clay content (%) as independent variables and GR₅₀ as a dependent variable, showed that organic carbon content (%) was a significant predictor of pyroxasulfone bioactivity in prairie soils (Table 3). This demonstrated that increased pyroxasulfone adsorption to organic matter decreased pyroxasulfone bioactivity and subsequently might reduce pyroxasulfone efficacy. These results agree with the findings reported for soils from Australia,⁴⁾ the United States,¹⁾ and Canada⁸⁾ where higher pyroxasulfone application rates were required to achieve effective weed control in soils containing higher levels of organic matter. Organic matter is colloidal in nature with a reactive surface capable of binding herbicide molecules, and consequently lowering the bioavailable herbicide concentration which has been shown for numerous herbicides.^{22–26)}

3. Effect of soil pH on pyroxasulfone bioactivity

The soils used in the evaluation of pyroxasulfone bioactivity described above had a broad range of organic carbon content (Table 1) that might have hindered revealing the effect of soil pH on pyroxasulfone bioactivity. Therefore, the effect of soil pH on pyroxasulfone bioactivity was examined separately after altering the natural soil pH. Alkalization and acidification yielded differ-

Fig. 4. Effect of soil pH on pyroxasulfone bioactivity in prairie soils determined by the 7-day sugar beet shoot length bioassay; each data point represents mean $\pm$ standard error; estimated equations are listed in Table 2.

ent increments in soil pH above and below the natural pH due to differences in buffering capacity of the soils. Alkalization with 0.2 g of CaCO₃ per 50 g of soil raised pH from 7.2 to 7.4 and from 5.0 to 6.4 in Haverhill clay loam and Scott loam, respectively, and did not increase soil pH in Haverhill loam as this soil had relatively high carbonate content and natural pH (Table 1). Acidification with 0.5 mL of 1 M HCl per 50 g of soil lowered pH from 7.9 to 7.6, from 7.2 to 4.8 and from 5.0 to 4.3 in Haverhill loam, Haverhill clay loam and Scott loam, respectively. Further acidification of Haverhill loam with 1 mL of 1 M HCl per 50 g of soil lowered pH of this soil to 7.4.

Table 4. Multiple regression analysis for pyroxasulfone dissipation half-lives and selected soil characteristics

Model	Coefficient ^{a)}	Standard error	p value ^{b)}
Constant	164.7	26.3	0.001
Organic carbon (%)	−10.8	5.5	0.034
Soil pH	−11.9	3.7	0.008
Clay (%)	−0.4	0.3	0.196

^{a)} Equation $y = 164.7 - 10.8 \times \text{OC}(\%) - 11.9 \times \text{soil pH} - 0.4 \times \text{clay}(\%)$; $R^2 = 0.851$; $F = 20.887$. ^{b)} Significance.

Sugar beet shoot length inhibition was reduced in acidified soils (Fig. 4), demonstrating that pyroxasulfone was less available to plants at lower soil pH. Alkalization increased sugar beet shoot length inhibition in Haverhill loam but did not change sugar beet response in Scott loam (Fig. 4), indicating that the effect of soil pH on pyroxasulfone bioactivity could vary with soil type. The GR_{50} values (Table 2) were correlated with soil pH in Haverhill loam ($R^2 = 0.96$) and in Haverhill clay loam ($R^2 = 0.93$) but not in Scott loam ($R^2 = 0.52$). These results demonstrated that pyroxasulfone bioactivity is generally sensitive to changes in soil pH and that pyroxasulfone may be less efficacious in soils of lower pH.

Usually soil pH affects both the dissociation of herbicide molecules and the charges of the organic matter and clay colloids. Pyroxasulfone molecule is not acidic because it does not contain dissociable hydrogen⁸⁾ (Fig. 1). Therefore, the effect of soil pH on pyroxasulfone bioactivity could be primarily related to the change in ionic charges on soil colloids. As soil pH decreases, there are fewer negative charges on organic and clay surfaces.²⁷⁾ Typically, this results in greater sorption of herbicides, and subsequently in reduced concentration of bioavailable herbicide in soil solution.^{25,26,28–30)}

4. Pyroxasulfone dissipation under laboratory conditions

Pyroxasulfone dissipation differed among the investigated soils (Fig. 5); the estimated half-lives ranged from 16 to 69 days and are comparable to reported half-lives from the literature.⁸⁾ Multiple regression analysis using organic carbon content (%), soil pH and clay content (%) as independent variables and half-life as a dependent variable, showed that organic carbon content (%) and soil pH were significant in affecting pyroxasulfone half-life in prairie soils (Table 4). Pyroxasulfone dissipation half-life was shorter when either organic carbon content or soil pH increased. Typically, high organic matter may either slow down herbicide dissipation by adsorption of a herbicide or may increase the rate of dissipation by providing an environment of enhanced microbial activity.³¹⁾ Because dissipation was faster in soils of high organic matter, it is therefore possible that the microbial activity associated with organic matter played an important role in pyroxasulfone degradation. However, the mechanism of pyroxasulfone degradation in soil was not investigated in this study since the objective was only to evaluate pyroxasulfone persistence in prairie soils. The more rapid pyroxasulfone dissipation at high soil pH was potentially related to increased pyroxasulfone bioactivity in soils with raised pH (see above), and consequently

Fig. 5. Pyroxasulfone dissipation determined by the 7-day sugar beet shoot length bioassay in prairie soils under laboratory conditions of 25°C and moisture content of 85% field capacity: Haverhill loam, $k = 0.015/\text{day}$, $T_{1/2} = 49$ days; Scott loam, $k = 0.010/\text{day}$, $T_{1/2} = 69$ days; Haverhill clay loam, $k = 0.023/\text{day}$, $T_{1/2} = 30$ days; Sutherland clay, $k = 0.043/\text{day}$, $T_{1/2} = 16$ days; Weyburn loam, $k = 0.014/\text{day}$, $T_{1/2} = 48$ days; each data point represents mean $\pm$ standard error.

increased pyroxasulfone concentration available in soil solution for decomposition. The results of this study showed that the rate of pyroxasulfone dissipation in prairie soils varied with soil type and was more rapid in soils of high organic matter and of high soil pH.

5. Pyroxasulfone and sulfentrazone interactions

The expected and observed dose–response curves obtained by measuring shoot length inhibition of sugar beet in response to combined pyroxasulfone and sulfentrazone in two soils are presented in Fig. 6. In Haverhill loam the expected shoot length inhibition was higher (at 0.05 significance level) than the observed inhibition demonstrating that the interaction between pyroxasulfone and sulfentrazone was antagonistic in this soil. In Haverhill clay loam the expected and observed values were not different indicating that the combined effect of pyroxasulfone and sulfentrazone was additive in this soil. In an antagonistic interaction the efficacy of the combined herbicides is reduced and consequently may result in decreased weed control, while in an additive interaction the efficacy is the sum activity of the combined herbicides.

Using herbicides with different mode of action either applied as pre-mixed combinations or applied in rotation reduces problems related to weed resistance and consequently improves

Fig. 6. Dose-response curves for pyroxasulfone in combination with sulfentrazone determined by the 7-day sugar beet shoot length bioassay; each data point represents mean $\pm$ standard error; estimated equations are listed in Table 2.

weed control. However, combinations of herbicides are generally chosen to broaden the spectrum of weed control without prior knowledge of the possible interactions between herbicides.²¹⁾ It has been reported that weed control with mixtures of pyroxasulfone and sulfentrazone in sunflower production across the Great Plains of the United States generally resulted in additive interactions between these two herbicides,⁶⁾ but antagonism was also observed with some plant species.¹³⁾ This study using sugar beet as a bioindicator plant showed that the interactions between pyroxasulfone and sulfentrazone may be either antagonistic or additive and that the nature of these interactions could be soil-dependent.

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