Weed Technology

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Preemergence and postemergence weed control in sweet corn on organic soils

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Research Article

Cite this article: Rodriguez AG, Sandhu HS, Wright AL, Odero DC (2023) Preemergence and postemergence weed control in sweet corn on organic soils. Weed Technol. **37**: 287–295. doi: 10.1017/wet.2023.35

Received: 3 October 2022
Revised: 5 April 2023
Accepted: 9 May 2023
First published online: 15 June 2023

Associate Editor:
David Johnson, Corteva Agriscience

Nomenclature:
Atrazine; bentazon; mesotrione; pyroxasulfone; *S*-metolachlor; tembotrione; topramezone; common lambsquarters; *Chenopodium album* L. CHEAL; common purslane; *Portulaca oleracea* L. POROL; fall panicum; *Panicum dichotomiflorum* Michx. PANDI; sweet corn; *Zea mays* spp. *saccharata*

Keywords:
Grass control; broadleaf weed control; mixtures; organic soil

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Abstract

Atrazine and *S*-metolachlor are the herbicides most relied on by growers to control weeds in sweet corn crops grown in the Everglades Agricultural Area (EAA) in southern Florida. Alternative weed management programs are needed. Field experiments were conducted in 2021 and 2022 to evaluate the efficacy of 1) pyroxasulfone (183 and 237 g ha^{-1}) alone or as a premix with carfentrazone-ethyl (13 and 17 g ha^{-1}) or fluthiacet-methyl (6 and 7 g ha^{-1}), *S*-metolachlor (1,790 g ha^{-1}) alone or in combination with atrazine (3,360 g ha^{-1}) applied preemergence(PRE); 2) mesotrione (105 g ha^{-1}), topramezone (25 g ha^{-1}), and tembotrione (92 g ha^{-1}) applied postemergence alone or in combination with atrazine (560 and 2,240 g ha^{-1}) or bentazon (1,120 g ha^{-1}); and 3) mechanical cultivation alone at the fourth and the fourth followed by the sixth leaf stages of sweet corn. PRE-applied herbicides did not provide acceptable control of fall panicum, common lambsquarters, or common purslane probably due to a lack of incorporation into the soil because of limited rainfall. POST-applied topramezone alone or in combination with atrazine or bentazon resulted in effective fall panicum control (>91%). Topramezone alone provided 83% and 88% control of common lambsquarters and common purslane, respectively, whereas atrazine added to topramezone resulted in >94% control of both weed species. Mesotrione and tembotrione plus atrazine provided excellent control (>93%) of both broadleaf weed species but poor fall panicum control (<72%). Mechanical cultivation alone did not effectively control any weeds. Overall, treatments that contained topramezone resulted in greater sweet corn yield. These results show that a combination of topramezone, mesotrione, and tembotrione with atrazine resulted in improved broadleaf weed control. Fall panicum control was improved only with the combination of topramezone with atrazine, showing that atrazine is an important mixture component of these herbicides to provide effective POST weed control in sweet corn on organic soils of the EAA.

Introduction

Sweet corn is a valuable crop cultivated on approximately 10,000 ha of organic soils or Histosols in the Everglades Agricultural Area (EAA) located south of Lake Okeechobee in southern Florida (USDA-NASS 2021b). The EAA is the largest contiguous body of organic soils in the United States and is used predominantly for sugarcane (*Saccharum* spp. hybrids) production. Sugarcane is cultivated in rotation with rice (*Oryza sativa* L.) and winter vegetables (including sweet corn) during the crop's fallow renovation period. The EAA Histosols are characterized by organic matter content of 80% to 90% (Wright and Hanlon 2019; Zelazny and Carlisle 1974). Weed interference is a major factor that limits sweet corn production in the EAA. Sweet corn weed management efforts used in the region include preemergence (PRE) and postemergence (POST) herbicides in combination with mechanical cultivation. Atrazine and *S*-metolachlor have been the foundation of PRE weed control efforts in sweet corn crops in the EAA (Odero and Wright 2013a). POST weed control has been accomplished using atrazine, which is effective on many broadleaf weeds, but it has limited activity against grasses (Shaner 2014). Mechanical cultivation between row middles and hilling are common practices used to supplement chemical weed control. Hilling is also used to enhance sweet corn anchoring and resistance to lodging. Cultivation can reduce the number of herbicide applications but does not provide sufficient weed control to completely replace chemical control (Colquhoun et al. 1999).

Atrazine is the most widely used herbicide in sweet corn production (USDA-NASS 2021a) because of its low cost, high efficacy, and residual activity on several weeds (Arslan et al. 2016; Swanton et al. 2007; Williams et al. 2010). Atrazine is usually mixed with other PRE and POST herbicides to broaden and improve season-long weed control. Mixing herbicides is a weed management practice that improves weed control and mitigates evolution of herbicide resistance by reducing selection pressure through diversification of herbicides with different modes of action (Damalas et al. 2017; Norsworthy et al. 2012). The mixture of PRE atrazine and *S*-metolachlor, the second most widely used herbicide in sweet corn (USDA-NASS 2021a), is commonly used in the EAA to provide broad spectrum weed control. Although *S*-metolachlor provides effective control of several grass weeds in corn crops, it has also demonstrated good activity against yellow nutsedge (*Cyperus esculentus* L.) and several broadleaf weed species (O'Connell et al. 1998). A combination of metolachlor with atrazine provided 94% to 100% control of common lambsquarters and common ragweed (*Ambrosia artemisiifolia* L.), and 27% to 75% control of ivyleaf morningglory (*Ipomoea hederacea* Jacq.) (Ferrell and Witt 2002). That study demonstrated inconsistent broadleaf weed control that can occasionally occur with the herbicide combination. In soils with high organic matter in the EAA, PRE weed control is generally more difficult to implement because of herbicide adsorption or metabolism by soil microorganisms (Schueneman and Sanchez 1994) resulting in the need for higher herbicide rates to provide efficacious weed control. Weed persistence and resulting yield reduction from weed interference is common in sweet corn crops in the EAA because of reduced efficacy and residual activity of atrazine and *S*-metolachlor. A shift to predominantly grass weed species, particularly fall panicum, in the EAA is attributed to the typical cropping system that involves a rotation of sweet corn with gramineous crops (i.e., sugarcane, rice), and has compounded weed management problems in the crop. In addition, overreliance on atrazine and its low efficacy on grass weeds has probably contributed to increased infestation of grasses in the cropping system. Currently, 244 and 3 confirmed cases of weeds resistant to atrazine and *S*-metolachlor, respectively, have been recorded (Heap 2022). Although no weeds have been confirmed to be resistant to these herbicides in the EAA, continued use of atrazine in particular faces an uncertain future in North America because of surface water contamination concerns (Swanton et al. 2007). Because the EAA is considered to be environmentally sensitive, the potential exists that contaminated water from cultivated fields may flow into and damage sensitive water conservation areas. Weed control in sweet corn on organic soils in the EAA can be improved through increased use of novel, efficacious broad-spectrum herbicides to reduce the overreliance on atrazine and *S*-metolachlor.

Pyroxasulfone is a PRE herbicide that can be integrated into weed control programs for sweet corn in the EAA. It is a very-long-chain fatty acid (VLCFA) elongase–inhibiting herbicide and is used for selective residual control of broadleaf and annual grass weeds in corn, wheat (*Triticum aestivum* L.), soybean (*Glycine max* L. Merr.), and sunflower (*Helianthus annuus* L.) crops (Anonymous 2021b; Boutsalis et al. 2014; Olson et al. 2011; Shaner 2014; Stephenson et al. 2017a, 2017b; Tanetani et al. 2009). Pyroxasulfone is a low-use-rate, relatively less water-soluble herbicide compared with other chloroacetamide VLCFA elongase–inhibiting herbicides such as *S*-metolachlor (Shaner 2014; Westra 2012). Pyroxasulfone provides better weed control at use rates lower than those of chloroacetamide herbicides (Steele et al. 2005; Yamaji et al. 2016). The efficacy and use rate of pyroxasulfone can be affected by edaphic factors. Westra (2012) reported a strong correlation between soil organic matter content and pyroxasulfone adsorption. Soil water solubility and adsorption have the potential to affect pyroxasulfone's efficacy. Yamaji et al. (2016) reported that pyroxasulfone at 200 to 300 g ha^{-1} provided acceptable weed control in soils with up to 3% organic matter content, and higher rates of pyroxasulfone may be required in soils with higher organic matter content. In contrast, Odero and Wright (2013b) reported that pyroxasulfone at 214 g ha^{-1} provided effective weed control in soils with 80% organic matter. Tolerance of sweet corn to pyroxasulfone with minimal transient phytotoxicity has been reported (Odero and Wright 2013b; Sikkema et al. 2008). Pyroxasulfone is marketed as a solo product (Anonymous 2021b) or as a premix with herbicides that inhibit protoporphyrinogen oxidase, such as carfentrazone-ethyl or fluthiacet-methyl (Anonymous 2021a). The premixes have dual modes of action and a flexible application window with the option of applying preplant, PRE, and early POST (Anonymous 2021a). Thus far, only three weeds are known to have evolved resistance to pyroxasulfone (Heap 2022).

The 4-hydroxyphenylpyruvate dioxygenase (HPPD)-inhibiting herbicides mesotrione, tembotrione, and topramezone have become widely used for POST broadleaf and grass weed control in sweet corn (Arslan et al. 2016; USDA-NASS 2021a). Mesotrione can be applied PRE and POST to control broadleaf weeds and some grasses (Dittmar et al. 2019; Shaner 2014). Odero and Wright (2013a) observed acceptable common lambsquarters control with PRE mesotrione incorporated with overhead irrigation following application. Sequential PRE applications of mesotrione followed by a POST application of mesotrione effectively controls several weed species (Armel et al. 2003). Previous research has shown that tembotrione and topramezone provide consistent control of a wide range of broadleaf and grass weed species (Bollman et al 2008; Damalas et al. 2017; Soltani et al. 2011; Stephenson et al. 2015). Topramezone and tembotrione provide control of a greater range of grasses than mesotrione (Bollman et al. 2008; Soltani et al. 2011). Furthermore, mixtures of these HPPD inhibitors with low rates of atrazine improved the efficacy of broadleaf weed control in sweet corn (Bollman et al. 2008; Williams et al. 2011). Bentazon is an atrazine alternative, a photosystem II inhibitor, used primarily for annual broadleaf control in graminaceous crops such as corn, rice, and sorghum [*Sorghum bicolor* (L.) Moench], but it also is used to control some perennials such as yellow nutsedge (Mine et al. 1975; Shaner 2014). Willemse et al. (2021) reported an additive interaction between mesotrione plus bentazon for the control of waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer] in corn.

Pyroxasulfone and the HPPD-inhibiting herbicides mesotrione, tembotrione, and topramezone are potential alternatives to atrazine and *S*-metolachlor for providing efficacious PRE and POST control of problematic weeds in sweet corn in the EAA. Thus, the objective of this research was to assess the efficacy of using pyroxasulfone, mesotrione, tembotrione, topramezone, and mechanical cultivation for weed control in sweet corn on organic soils in the EAA and to compare those herbicides to the commonly used combination of atrazine and *S*-metolachlor.

Materials and Methods

Site Description

Field experiments were conducted at the University of Florida Everglades Research and Education Center in Belle Glade, FL (26.6584°N, 80.6250°W) in 2021 and 2022. The soil type was Dania Muck (Euic, hyperthermic, shallow Lithic Haplosaprists), pH 7.4, and with 85% organic matter. Soil pH and organic matter content were determined using the method described by Fernandez et al. (2019). Experimental fields were prepared using conventional agronomic practices. Sweet corn 'BSS1075' (Syngenta, Greensboro, NC) was planted at 76.2-cm interrow and 16-cm intrarow spacings at a seeding rate of 80,700 seeds ha^{-1} on February 8, 2021, and February 11, 2022. Fertilizer 11-37-0 was applied at 37 kg N ha^{-1} and 125 kg P_2O_5 ha^{-1} at planting. Insect pests and diseases were

Table 1. Herbicides, manufacturers, rates, timing of application, and cultivation.[a,b]

Herbicides				
Common name	Trade name	Manufacturer	Rate	Timing[c]
			g ha^{-1}	
Pyroxasulfone	Zidua® SC	BASF Corporation, Research Triangle Park, NC	183	PRE
Pyroxasulfone	Zidua® SC		237	PRE
Pyroxasulfone + carfentrazone-ethyl	Anthem® Flex	FMC Corporation, Philadelphia, PA	183 + 13	PRE
Pyroxasulfone + carfentrazone-ethyl	Anthem® Flex		237 + 17	PRE
Pyroxasulfone + fluthiacet-methyl	Anthem® Maxx	FMC Corporation, Philadelphia, PA	183 + 6	PRE
Pyroxasulfone + fluthiacet-methyl	Anthem® Maxx		237 + 7	PRE
S-metolachlor	Dual II Magnum®	Syngenta Crop Protection, LLC, Greensboro, NC	1,790	PRE
S-metolachlor + atrazine	Dual II Magnum® + Atrazine 4L	Loveland Products, Inc., Greeley, CO	1,790 + 3,360	PRE
Mesotrione[d]	Callisto®	Syngenta Crop Protection, LLC, Greensboro, NC	105	POST
Mesotrione + atrazine	Callisto® + Atrazine 4L		105 + 560	POST
Mesotrione + atrazine	Callisto® + Atrazine 4L		105 + 2,240	POST
Mesotrione + bentazon	Callisto® + Basagran®	Winfield Solutions, LLC, St. Paul, MN	105 + 1,120	POST
Topramezone[e]	Armezon®	BASF Corporation, Research Triangle Park, NC	25	POST
Topramezone + atrazine	Armezon® + Atrazine 4L		25 + 560	POST
Topramezone + atrazine	Armezon® + Atrazine 4L		25 + 2,240	POST
Topramezone + bentazon	Armezon® + Basagran®		25 + 1,120	POST
Tembotrione[e]	Laudis®	Bayer CropScience LP, St. Louis, MO	92	POST
Tembotrione + atrazine	Laudis® + Atrazine 4L		92 + 560	POST
Tembotrione + atrazine	Laudis® + Atrazine 4L		92 + 2,240	POST
Tembotrione + bentazon	Laudis® + Basagran®		92 + 1,120	POST
Cultivation 1×			–	V4
Cultivation 2×			–	V4 fb V6

[a]Abbreviations: fb, followed by; POST, postemergence; PRE, preemergence; V4, fourth leaf stage of sweet corn growth; V6, sixth leaf stage of sweet corn growth.
[b]Studies were carried out on sweet corn crops in Belle Glade, FL, in 2021 and 2022.
[c]PRE applied immediately after planting prior to crop emergence, POST applied at the V4 stage of sweet corn growth, one cultivation (1×) performed at the V4 stage of sweet corn growth, and two cultivations (2×) performed at the V4 followed by the V6 stage of sweet corn growth.
[d]Mesotrione treatments included a nonionic surfactant at 0.25% v/v (Activator 90; Loveland Products Inc., Greeley, CO).
[e]Topramezone and tembotrione treatments included methylated seed oil at 1% v/v (Dyne-Amic®; Helena Chemical Co., Collierville, TN) and ammonium sulfate at 1.2% wt/v (S-Sul® Sprayable Ammonium Sulfate; American Plant Food Corp., Galena Park, TX).

conventionally managed based on standard sweet corn pest management practices for the region.

Experimental Design and Treatments

The experiment was a randomized complete block design with four replications. Plots were four rows wide (3.0 m wide) by 7.6 m long. A total of 22 weed control treatments were assessed, including PRE treatments containing pyroxasulfone, *S*-metolachlor, and atrazine; POST treatments containing mesotrione, topramezone, tembotrione, atrazine, and bentazon; and mechanical cultivation (Table 1). Nontreated, weed-free (hand weeded) and weedy controls were included for comparison. Conventional cultivation of the experimental fields prior to planting controlled any previously emerged weeds. PRE treatments were applied immediately after planting prior to crop emergence, and POST treatments were applied at the fourth leaf stage of sweet corn growth. Weeds ranged from 2.5 to 7.6 cm tall at POST treatment application. Mechanical cultivation was performed at the fourth and fourth followed by the sixth leaf stages of sweet corn growth. All mesotrione treatments and combinations included a nonionic surfactant (Activator 90; Loveland Products Inc., Greeley, CO) at 0.25% v/v, while topramezone and tembotrione treatments and combinations included methylated seed oil (Dyne-Amic®; Helena Chemical Co., Collierville, TN) at 1% v/v and ammonium sulfate (S-Sul® Sprayable Ammonium Sulfate; American Plant Food Corp., Galena Park, TX) at 1.2% wt/v. Herbicide treatments were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 187 L ha^{-1} at 276 kPa using TeeJet® XR11002VS nozzle tips (Spraying Systems Co., Wheaton, IL) at a walking speed of 4.8 km h^{-1}.

Data Collection

Sweet corn stand count was taken 15 to 25 d after planting from the middle two rows in each plot. Visual estimation of sweet corn injury and weed control occurred at 14, 28, and 42 d after POST treatment (DAPT; equivalent to 28, 42, and 56 d after PRE application) using a scale of 0% to 100%, with 0% being no injury or weed control and 100% being complete plant death or weed control. Weed control assessments were conducted for each individual weed species present in the experimental fields. The most prevalent weeds were fall panicum at densities of 192 and 86 plants m^{-2}, common lambsquarters at 54 and 32 plants m^{-2}, and common purslane at 21 and 2 plants m^{-2} in 2021 and 2022, respectively. The corn ears of the middle two rows in each plot were harvested by hand, shucked, silked, and weighed at maturity, and marketable yield was recorded on April 26, 2021, and April 29, 2022, for the February 8, 2021, and February 11, 2022, plantings, respectively. Sweet corn ears were considered marketable when 90% of kernels were full, yellow, well-trimmed; free from insect, disease, and bird damage; and with the length of each cob not less than 15.2 cm (USDA-AMS 1992).

Statistical Analysis

Data were subjected to ANOVA using the LME4 package (Bates et al. 2022) of the R statistical language (version 4.1.0; R Core Team 2022). Weed control and sweet corn yield were analyzed using a mixed-effects model with the *lmer* function in the LME4 package. Treatment program was considered a fixed effect, while year and replication nested within year were considered as random effects. Weed control for each evaluation timing was analyzed separately

Table 2. Fall panicum control and sweet corn yield in response to preemergence and postemergence herbicides.[a,b,c]

Treatment	Rate	Time[d]	Fall panicum control[e] 14 DAPT		28 DAPT		42 DAPT		Sweet corn yield	
	g ha^{-1}		%						kg ha^{-1} × 1,000	
Nontreated control[f]									5.2	a
Hand weeded control[f]									12.7	c
Pyroxasulfone	183	PRE	65	a-d	64	a-f	63	abc	9.2	abc
Pyroxasulfone	237	PRE	76	c-f	70	c-g	72	bcd	11.1	bc
Pyroxasulfone + carfentrazone-ethyl	183 + 13	PRE	65	a-d	60	a-e	53	ab	9.9	abc
Pyroxasulfone + carfentrazone-ethyl	237 + 17	PRE	66	a-d	66	b-f	59	ab	10.6	bc
Pyroxasulfone + fluthiacet-methyl	183 + 6	PRE	73	b-f	61	a-e	73	bcd	9.9	abc
Pyroxasulfone + fluthiacet-methyl	237 + 7	PRE	73	b-f	74	d-g	72	bcd	11.1	bc
S-metolachlor	1,790	PRE	71	b-f	54	a-e	71	bcd	7.4	ab
S-metolachlor + atrazine	1,790 + 3,360	PRE	68	a-e	66	b-f	68	a-d	8.8	abc
Mesotrione	105	POST	47	a	42	a	43	a	7.2	ab
Mesotrione + atrazine	105 + 560	POST	51	ab	46	ab	42	a	9.0	abc
Mesotrione + atrazine	105 + 2,240	POST	58	abc	51	a-d	49	ab	11.2	bc
Mesotrione + bentazon	105 + 1,120	POST	59	abc	54	a-e	49	ab	8.9	abc
Topramezone	25	POST	93	f	89	g	91	d	11.2	bc
Topramezone + atrazine	25 + 560	POST	93	f	85	fg	91	d	11.3	bc
Topramezone + atrazine	25 + 2,240	POST	91	ef	89	g	91	d	11.6	bc
Topramezone + bentazon	25 + 1,120	POST	88	def	86	fg	89	cd	11.5	bc
Tembotrione	92	POST	56	abc	50	abc	45	ab	9.5	abc
Tembotrione + atrazine	92 + 560	POST	71	b-f	63	a-f	58	ab	10.9	bc
Tembotrione + atrazine	92 + 2,240	POST	77	c-f	70	c-g	72	bcd	9.8	abc
Tembotrione + bentazon	92 + 1,120	POST	77	c-f	66	b-f	66	a-d	9.0	abc
Cultivation 1×	183	V4	68	a-e	59	a-e	57	ab	9.1	abc
Cultivation 2×	237	V4 fb V6	73	b-f	75	efg	72	bcd	9.9	abc

[a]Abbreviations: DAPT, days after postemergence treatment; fb, followed by; POST, postemergence; PRE, preemergence; V4, fourth leaf stage of sweet corn growth; V6, sixth leaf stage of sweet corn growth.
[b]Studies were carried out in Belle Glade, FL, in 2021 and 2022. Data for both years are combined.
[c]Means followed by the same letter within a column are not significantly different according to Tukey's test (P < 0.05).
[d]PRE herbicides applied immediately after planting prior to crop emergence, POST herbicides applied at the V4 stage of sweet corn growth, one cultivation (1×) performed at the V4 stage of sweet corn growth, and two cultivations (2×) performed at the V4 followed by the V6 stage of sweet corn growth.
[e]Fall panicum control: 14, 28, and 42 DAPT equivalent to 28, 42, and 56 d after PRE herbicide application.
[f]Nontreated (weedy) and hand weeded (weed-free) control data were not included in the analysis because there was no variance.

for each weed species, and the nontreated weed-free and weedy control data were excluded from the analysis because there was no variance. ANOVA assumptions of normality of residuals and homogeneity of variance were tested using the *Shapiro.test* and *Bartlett.test* functions in the base package of R, respectively. Data were transformed when necessary. Estimated marginal means were calculated and the post hoc Tukey test was performed for all pairwise treatment comparisons (P < 0.05) using the *eemeans* function in the EMMEANS package of R (Lenth 2022) and the *cld* function in the MULTICOMP package of R (Hothorn 2022). Contrasts were used to compare groups of different weed control treatments (P < 0.05) with respect to weed control and sweet corn yield using the *contrasts* function in the base package of R.

Results and Discussion

Totals of 93 and 65 mm of rainfall were received in 2021 and 2022 growing seasons, respectively (FAWN 2022). Just 1 mm of rain fell 3 d before PRE herbicide treatments were applied in 2021 compared with 9 mm that fell in 2022. A total of 9 and 12 mm of rain fell within the first 7 d after PRE herbicides were applied in 2021 and 2022, respectively. In addition, 2 mm of rain fell between 8 and 14 d after application in 2021, while only 0.25 mm fell in the same period in 2022. Rainfall within the first 7 to 14 d after application is important for enhancing the efficacy of PRE herbicides (Buhler 1991; Chomas and Kells 2004; Salzman and Renner 1992). Average rainfall in February from 2010 to 2020 was 39 mm (FAWN 2022), whereas 25 and 24 mm of rain fell in February 2021 and 2022, respectively. A total of 53 mm of rain fell in the last 21 d of 2021 compared with 11 mm in 2022, when silking to the milk stage of sweet corn growth occurred.

Fall Panicum Control

The main effect of herbicide treatment program was significant for fall panicum control at all evaluation timings (P < 0.05). All PRE herbicide treatments provided inadequate control of fall panicum throughout the growing season, and the treatments were not significantly different (Table 2). Fall panicum control following PRE herbicide application ranged from 65% to 76%, 54% to 74%, and 53% to 73% at 14, 28, and 42 DAPT, respectively. No significant differences were observed between pyroxasulfone and *S*-metolachlor treatments at 42 DAPT. Treatments containing pyroxasulfone and *S*-metolachlor provided 53% to 73% and 68% to 71% control of fall panicum at 42 DAPT, respectively. Pyroxasulfone applied alone at 183 and 237 g ha^{-1} provided 63% and 72%, respectively, control of fall panicum at 42 DAPT (at canopy closure). Steele et al. (2005) found that applying pyroxasulfone at 250 g ha^{-1} provided 91% control of Texas panicum (*Panicum texanum* Buckley) at 28 d after application in soils with 1% organic matter; however, pyroxasulfone at 500 g ha^{-1} was required to maintain control greater than 90% at 63 d after application. In addition, pyroxasulfone at 125 and 250 g ha^{-1} has been shown to provide effective control of grass weeds such as barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.], green foxtail

https://doi.org/10.1017/wet.2023.35 Published online by Cambridge University Press

[*Setaria viridis* (L.) P. Beauv.], and browntop millet [*Urochloa ramosa* (L.) Nguyen] in soils with up to 2.7% organic matter (Geier et al. 2006; Stephenson et al. 2017b; Yamaji et al. 2014). Knezevic et al. (2009) reported that higher rates of pyroxasulfone were required to provide effective control of green foxtail as organic matter content increased. The addition of carfentrazone-ethyl or fluthiacet-methyl to pyroxasulfone did not significantly increase fall panicum control throughout the season regardless of rate (Table 2). Similarly, pyroxasulfone plus fluthiacet-methyl did not improve control of barnyardgrass or browntop millet compared with pyroxasulfone applied alone (Hardwick 2013). In contrast, Grichar et al. (2021) reported increased control of Texas millet [*U. texana* (Buckley) R. Webster] with the premix of pyroxasulfone plus carfentrazone-ethyl; however, sequential POST herbicide applications were needed to provide season-long control. *S*-metolachlor (1,790 g ha^{-1}) alone applied PRE provided similar fall panicum control (71%) compared to pyroxasulfone applied alone, and no benefit was gained by mixing *S*-metolachlor with atrazine at 3,360 g ha^{-1} (Table 2). O'Connell et al. (1998) reported that *S*-metolachlor at rates as low as 1,200 g ha^{-1} provided an average of 91% control of grass weeds such as large crabgrass [*Digitaria sanguinalis* (L.) Scop.], barnyardgrass, *Setaria* spp., and johnsongrass [*Sorghum halepense* (L.) Pers.] in soils with up to 5% organic matter.

PRE herbicides must be incorporated into the soil shortly after being applied because weed control efficacy depends on activation by soil moisture (Ferreira et al. 2021). According to a report by Landau et al. (2021), 50 to 100 mm of rain after PRE application of atrazine, acetochlor, *S*-metolachlor, and mesotrione is required for successful weed control, and little or no rain within the first 15 d can significantly affect the efficacy of these PRE herbicides. Janak and Grichar (2016) reported that control of browntop signalgrass (*Panicum fasciculatum* Sw.) following application of *S*-metolachlor and atrazine was reduced when <50 mm of rain fell during the first 14 d after treatment. Furthermore, low soil moisture can reduce pyroxasulfone efficacy by reducing its availability for plant uptake and contact with emerging weeds (Ferreira et al. 2021). In our study, 11 and 12 mm of rain fell within the first 15 d after PRE herbicide applications in 2021 and 2022, respectively (FAWN 2022). Thus, poor weed control following PRE herbicide treatments in this study may be related to limited rain, which was needed for herbicide incorporation during the critical first 15 d after application.

POST herbicides provided 47% to 93%, 42% to 89%, and 42% to 91% control of fall panicum at 14, 28, and 42 DAPT, respectively. Mechanical cultivation provided 68% to 73%, 59% to 75%, and 57% to 72% control of fall panicum at 14, 28, and 42 DAPT, respectively, with two cultivation passes providing better control. Fall panicum was controlled by 89% to 91% by topramezone applied alone or in combination with atrazine or bentazon at 42 DAPT, whereas 45% to 66% and 43% to 49% control was achieved by using tembotrione and mesotrione, respectively. POST treatments containing topramezone provided 25% and 26% greater fall panicum control than PRE-applied pyroxasulfone or cultivation at 42 DAPT, respectively (Table 3). Furthermore, among the herbicides that work as HPPD inhibitors, topramezone provided 45% greater fall panicum control compared to mesotrione, and 30% greater control compared to tembotrione treatments (Table 3). Topramezone treatments enhanced fall panicum control 89<)%) compared with a single cultivation (57%) at 42 DAPT (Table 2). However, it was not significantly different than control that occurred after a second cultivation (72%). Topramezone alone (25 g ha^{-1}) provided excellent fall panicum control (91%) at 42 DAPT; 46% and 44% greater than control following applications of tembotrione and mesotrione alone (Table 2). Bollman et al. (2008) reported that topramezone and tembotrione provided better control of grass weeds compared to mesotrione alone or in combination with atrazine. Soltani et al. (2011) reported that topramezone was more efficacious in controlling annual grasses than mesotrione; however, it did not provide consistent control of fall panicum. Poor control of fall panicum and other grass weed species following mesotrione applications has been previously reported in field corn, where mesotrione applied POST provided <63% control in a no-till cropping system (Armel et al. 2003). Mixtures of each HPPD-inhibitor herbicide with atrazine at 560 and 2,260 g ha^{-1}, and with bentazon at 1,120 g ha^{-1}, did not significantly differ in fall panicum control compared to the corresponding herbicide applied alone (Table 2). Williams et al. (2011) reported that adding atrazine at 1,120 g ha^{-1} to tembotrione at 31 g ha^{-1} improved grass control compared to tembotrione alone. Despite the nonsignificant differences observed in our study, tembotrione plus atrazine at 2,260 g ha^{-1} provided 27% greater control than tembotrione alone, which provided only 49% control (Table 2).

Single degree of freedom contrasts were conducted to determine whether differences existed in fall panicum control with the various herbicide combinations and cultivation (Table 3). No significant differences were detected when PRE, POST, and cultivation treatments are compared for their ability to control fall panicum at canopy closure (42 DAPT). However, topramezone treatments provided superior fall panicum control compared to other treatments (Table 3). Use of topramezone resulted in 25%, 45%, 30%, and 25% greater control of fall panicum at 42 DAPT compared to pyroxasulfone, mesotrione, tembotrione, and cultivation treatments, respectively. These results show that acceptable fall panicum control on organic soils of the EAA can be achieved by using topramezone as a POST treatment at the fourth-leaf stage of sweet corn.

Broadleaf Weed Control

There was an herbicide treatment effect on common lambsquarters and common purslane control at all evaluation timings ($P < 0.05$). PRE herbicide treatments that contained pyroxasulfone resulted in inconsistent control of broadleaf weed species, providing 37% to 66% and 61% to 74% control of common lambsquarters and common purslane, respectively, at 42 DAPT (Table 4). Pyroxasulfone applied alone did not provide acceptable broadleaf weed control, resulting in <57% common lambsquarters control and <64% common purslane control at 42 DAPT. The higher rate of pyroxasulfone at 237 g ha^{-1} did not result in improved control of either species. In contrast, Odero and Wright (2013a) observed excellent control of common lambsquarters and common purslane when pyroxasulfone was applied at 237 g ha^{-1} in soils with 80% organic matter. Furthermore, 217 to 271 g ha^{-1} of pyroxasulfone was required for successful control of common lambsquarters, common purslane, and spiny amaranth (*Amaranthus spinosus* L.) (Odero and Wright 2013b). In that study, an average of 51 mm of rainfall fell during the first 15 d after application, compared with an average of 17 mm in the present study. The premixes of pyroxasulfone with carfentrazone-ethyl and fluthiacet-methyl did not significantly increase control of common lambsquarters and common purslane compared to pyroxasulfone applied alone. However, common lambsquarters control was significantly greater

Table 3. Herbicide combination differences on weed control at 42 d after postemergence treatment (equivalent to 56 d after preemergence application) and sweet corn yield.[a,b,c,d]

Comparison	Fall panicum		Common lambsquarters		Common purslane		Sweet corn yield	
	Difference	P > |t|	Difference	P > |t|	Difference	P > |t|	Difference	P > |t|
	%		%		%		kg ha^{-1} × 1,000	
PRE vs POST	1	NS	−38	<0.0001	−25	<0.0001	−0.3	NS
PRE vs Cultivation	2	NS	−2	NS	12	0.0211	0.3	NS
POST vs Cultivation	1	NS	37	<0.0001	37	<0.0001	0.6	NS
Pyroxasulfone vs *S*-metolachlor	−4	NS	9	NS	1	NS	2.2	NS
Pyroxasulfone vs topramezone	−25	<0.0001	−33	<0.0001	−24	<0.0001	−1.1	NS
Pyroxasulfone vs mesotrione	20	<0.0001	−39	<0.0001	−23	<0.0001	1.2	NS
Pyroxasulfone vs tembotrione	5	NS	−36	<0.0001	−26	<0.0001	0.5	NS
Pyroxasulfone vs cultivation	1	NS	1	NS	13	NS	0.8	NS
Topramezone vs mesotrione	45	<0.0001	−6	NS	1	NS	2.3	0.0241
Topramezone vs tembotrione	30	<0.0001	−2	NS	−2	NS	1.6	NS
Mesotrione vs tembotrione	−15	0.0044	3	NS	−3	NS	−0.7	NS
Topramezone vs cultivation	26	<0.0001	34	<0.0001	37	<0.0001	1.8	NS
Mesotrione vs cultivation	−19	0.0026	44	<0.0001	35	<0.0001	−0.4	NS
Tembotrione vs cultivation	−4	NS	36	<0.0001	39	<0.0001	0.3	NS

[a]Abbreviations: NS, not significant; POST, postemergence; PRE, preemergence.
[b]Studies were carried out in Belle Glade, FL, in 2021 and 2022. Data for both years are combined.
[c]A positive number means the first factor of the comparison was superior, a negative number means the second factor was superior.
[d]Contrasts comparing groups of different weed control treatment programs (calculated as mean of all treatments that contained the treatment program). Contrasts were not significant (NS) at $P < 0.05$.

with pyroxasulfone plus fluthiacet-methyl at 7 g ha^{-1} (66%) compared to *S*-metolachlor applied alone (37%; Table 4). Similarly, Odero and Wright (2013a) reported poor control (<42%) of common lambsquarters with *S*-metolachlor at 49 d after application. Adding atrazine at 3,360 g ha^{-1} to *S*-metolachlor, compared to *S*-metolachlor applied alone, did not result in a significant increase in control of common lambsquarters or common purslane. These results are consistent with those reported by Swanton et al. (2007), who noted that atrazine plus *S*-metolachlor failed to control common lambsquarters and common purslane. In contrast, Whaley et al. (2009) reported 99% control of common lambsquarters with *S*-metolachlor plus atrazine. Adequate rainfall is required within the first 15 d after application for PRE herbicides to be activated (Janak and Grichar 2016; Landau et al. 2021). Poor weed control when rainfall is limited is caused by low bioavailability of the PRE herbicides in the soil (Landau et al. 2021). The low efficacy of pyroxasulfone and *S*-metolachlor observed in the present study was probably attributed to low rainfall and soil moisture during the first 15 d after application.

HPPD-inhibitor herbicides mesotrione, topramezone, and tembotrione applied POST provided acceptable control of broadleaf weed species at 42 DAPT, ranging from 83% to 97%, and 76% to 96% control of common lambsquarters and common purslane, respectively (Table 4). All POST herbicide combinations provided significantly greater (>27%) control of broadleaf weed species compared to cultivation treatments, except for common purslane control with mesotrione alone, topramezone alone, and topramezone plus bentazon; and common lambsquarters control with tembotrione alone, topramezone alone, and topramezone plus bentazon (Table 4). Adding bentazon and atrazine to the HPPD-inhibitor herbicides did not significantly improve control of the broadleaf weeds (Table 4). Mesotrione alone or in combination with atrazine or bentazon provided >93% common lambsquarters control. However, mesotrione alone provided only 76% control of common purslane, whereas its combination with atrazine at 560 and 2,240 g ha^{-1} provided 93% and 96% control, respectively. Similarly, Arslan et al. (2016) reported that mesotrione plus atrazine provided excellent control of problematic broadleaf weed species in sweet corn. Additive responses on broadleaf weed control have been reported when topramezone, mesotrione, and tembotrione were mixed with atrazine (Arslan et al. 2016; Bollman et al. 2008; Swanton et al. 2007). However, Arslan et al. (2016) observed that adding atrazine to tembotrione was not necessary to provide consistent broadleaf weed control. Similarly, our results suggest that tembotrione provides effective broadleaf weed control when applied alone (>89% at 42 DAPT; Table 4).

Similar to fall panicum, single degree of freedom contrasts were conducted to determine whether differences existed in control of common lambsquarters and common purslane with the various herbicide combinations and cultivation (Table 3). There were no differences in control of either broadleaf weed with the HPPD-inhibitor herbicides. PRE herbicides provided 38% and 25% less control of common lambsquarters and common purslane, respectively, compared to POST herbicides. POST herbicides provided 34% greater control of common lambsquarters and common purslane compared with that provided by mechanical cultivation. In contrast, cultivation resulted in 12% greater control of common purslane compared to the PRE herbicide combinations.

Sweet Corn Tolerance to Treatment Combinations and Yield

Sweet corn stand was not significantly different among treatments (data not presented). Pyroxasulfone applied PRE alone or as a premix with carfentrazone-ethyl or fluthiacet-methyl did not result in any visible sweet corn injury. Similarly, sweet corn exhibited no injury following a PRE application of *S*-metolachlor alone or in combination with atrazine. Sweet corn injury from pyroxasulfone has been reported on coarse-textured soils (Nurse et al. 2011). Odero and Wright (2013b) reported no injury to sweet corn with pyroxasulfone applied at up to 1,000 g ha^{-1} on fine-textured soil with 80% organic matter. Sikkema et al. (2008) reported tolerance of several sweet corn hybrids to pyroxasulfone at 209 and 418 g ha^{-1} on fine-textured soils with 3.7% to 9.2% organic matter. The HPPD-inhibitor herbicides mesotrione, topramezone, and

Table 4. Common lambsquarters and common purslane control in response to preemergence and postemergence herbicide programs applied to sweet corn crops.[a,b,c]

Treatment	Rate	Time[d]	Common lambsquarters control[e]			Common purslane control[e]		
			14 DAPT	28 DAPT	42 DAPT	14 DAPT	28 DAPT	42 DAPT
	g ha^{-1}		—————————————————————— % ——————————————————————					
Nontreated control[f]								
Hand weeded control[f]								
Pyroxasulfone	183	PRE	73 bcd	62 b-f	57 abc	69 a-d	67 a-d	64 a-e
Pyroxasulfone	237	PRE	76 b-f	60 bcd	53 ab	79 c-g	72 b-e	63 a-d
Pyroxasulfone + carfentrazone-ethyl	183 + 13	PRE	71 a-d	60 b-e	52 ab	73 a-e	77 b-g	67 a-g
Pyroxasulfone + carfentrazone-ethyl	237 + 17	PRE	71 a-d	61 b-e	55 ab	78 b-g	76 b-g	70 a-g
Pyroxasulfone + fluthiacet-methyl	183 + 6	PRE	63 abc	49 ab	52 ab	79 c-g	73 b-f	66 a-f
Pyroxasulfone + fluthiacet-methyl	237 + 7	PRE	84 c-g	75 c-g	66 b-e	75 a-f	82 b-g	74 a-g
S-metolachlor	1,790	PRE	50 a	30 a	37 a	70 a-d	58 ab	61 abc
S-metolachlor + atrazine	1,790 + 3,360	PRE	75 b-e	59 bc	57 abc	87 d-g	76 b-g	71 a-g
Mesotrione	105	POST	89 d-g	81 c-h	93 f	59 abc	58 ab	76 a-g
Mesotrione + atrazine	105 + 560	POST	93 d-g	93 gh	96 f	86 d-g	93 efg	93 d-g
Mesotrione + atrazine	105 + 2,240	POST	100 g	99 h	97 f	100 g	99 g	96 g
Mesotrione + bentazon	105 + 1,120	POST	100 g	94 gh	94 f	100 g	98 fg	94 efg
Topramezone	25	POST	99 fg	83 d-h	83 c-f	96 efg	83 c-g	88 b-g
Topramezone + atrazine	25 + 560	POST	100 g	92 gh	95 f	99 fg	89 d-g	94 efg
Topramezone + atrazine	25 + 2,240	POST	100 g	95 gh	96 f	100 g	95 efg	95 fg
Topramezone + bentazon	25 + 1,120	POST	99 g	83 e-h	83 c-f	99 fg	86 d-g	87 b-g
Tembotrione	92	POST	98 efg	84 fgh	90 ef	89 d-g	83 b-g	89 c-g
Tembotrione + atrazine	92 + 560	POST	100 g	93 gh	93 f	100 g	94 efg	96 g
Tembotrione + atrazine	92 + 2,240	POST	100 g	97 gh	94 f	100 g	97 efg	94 fg
Tembotrione + bentazon	92 + 1,120	POST	100 g	93 gh	89 def	100 g	94 efg	93 d-g
Cultivation 1×		V4	56 ab	44 ab	48 ab	52 a	43 a	50 a
Cultivation 2×		V4 fb V6	57 ab	65 b-f	63 a-d	54 ab	59 abc	59 ab

[a]Abbreviations: DAPT, days after postemergence treatment; fb, followed by; POST, postemergence; PRE, preemergence; V4, fourth leaf stage of sweet corn growth; V6, sixth leaf stage of sweet corn growth.
[b]Studies were carried out in Belle Glade, FL, in 2021 and 2022. Data for both years are combined.
[c]Means followed by the same letter within a column are not significantly different according to Tukey's test ($P < 0.05$).
[d]PRE herbicides applied immediately after planting prior to crop emergence, POST herbicides applied at the V4 stage of sweet corn growth, one cultivation (1×) performed at the V4 stage of sweet corn growth, and two cultivations (2×) performed at the V4 followed by the V6 stage of sweet corn growth.
[e]Common lambsquarters and common purslane control: 14, 28, and 42 DAPT equivalent to 28, 42, and 56 d after PRE herbicide application.
[f]Nontreated (weedy) and hand weeded (weed-free) control data were not included in the analysis because there was no variance.

tembotrione did not cause sweet corn injury in either growing season. However, the addition of bentazon to topramezone and tembotrione in 2022 resulted in injury exhibited as chlorosis of leaves 7 d after application. The observed injury (10%) was transient and was not observed 28 DAPT. Bollman et al. (2008) reported tolerance of sweet corn hybrids to topramezone and tembotrione, but differential tolerance to mesotrione.

Sweet corn yield for season-long weed-free control was 12,719 kg ha^{-1} (Table 2). The yield after all herbicide treatments was not significantly different from that of the season-long weed-free control (hand weeded) with the exception of PRE-only *S*-metolachlor and POST-only mesotrione (Table 2). PRE *S*-metolachlor and POST mesotrione applied alone resulted in 42% and 43% yield reduction, respectively, compared to the season-long weed-free control. The significant yield reduction observed from these herbicide treatments was attributed to poor weed control, particularly fall panicum. Season-long weed interference (the nontreated control) resulted in a 60% yield reduction compared to the season-long weed-free control (Table 2). Overall, topramezone treatment combinations resulted in significantly greater sweet corn yield compared to that of mesotrione combinations (Table 3). No significant differences in yield were observed for contrasts of other treatments (Table 3).

Reduced weed control by the standard PRE application of *S*-metolachlor plus atrazine was confirmed in this study. This warrants the need for alternatives to this herbicide combination so as to provide efficacious residual control of problematic weeds in sweet corn on organic soils in the EAA. The use of PRE-applied pyroxasulfone did not result in acceptable season-long control of problematic weed species in sweet corn in the EAA probably because of limited and erratic rainfall that may have resulted in decreased efficacy of the herbicide. Additionally, higher rates of pyroxasulfone may be needed to provide efficacious weed control in soils with high amounts of organic matter, particularly during periods of limited rainfall at sweet corn planting. Therefore, when sweet corn is planted in the EAA when soil moisture is limited, POST instead of PRE herbicides is recommended to provide effective weed control. Overall, cultivation as the sole weed control method is not effective, implying that a POST herbicide is needed to supplement cultivation for efficacious season-long weed control. Results from this study show that a combination of topramezone and atrazine (560 g ha^{-1}) applied at the fourth leaf stage of sweet corn when weeds are <7.6 cm tall will provide acceptable control of problematic grass and broadleaf weed species on the high organic soils of the EAA and result in no significant yield reduction. Increasing the atrazine rate to 2,260 g ha^{-1} in combination with topramezone does not provide any weed control or yield benefit in these studies. Topramezone applied without atrazine suppressed the growth of common lambsquarters (83%) and common purslane (88%). Mesotrione and tembotrione plus atrazine provided efficacious control of the broadleaf weed species but poor fall panicum control. The addition of atrazine to HPPD-inhibitor herbicides did not result in any antagonistic weed control effect. Based on results of this study, atrazine still plays an important role in weed management in sweet corn grown in the EAA when mixed with HPPD-inhibitor herbicides, and its

https://doi.org/10.1017/wet.2023.35 Published online by Cambridge University Press

exclusion may compromise the efficacy of weed control programs that involve mesotrione and tembotrione.

Practical Implications

Weed management is a major cost and challenge for growers of sweet corn, particularly on organic soils in southern Florida where growers rely on PRE and POST herbicides for weed control. Mechanical cultivation remains common in many sweet corn fields to supplement herbicide application and for hilling to enhance sweet corn anchoring and resistance to lodging. Atrazine and *S*-metolachlor have been the foundation of weed control efforts in sweet corn on organic soils. Weed persistence and resulting yield reduction from weed interference is common on organic soils because of reduced efficacy and the residual effect of these herbicides. Pyroxasulfone applied PRE, and mesotrione, tembotrione, and topramezone applied POST, are potential alternatives to atrazine and *S*-metolachlor to provide effective control of problematic weeds in sweet corn crops. Overall, PRE-applied pyroxasulfone did not result in acceptable control of problematic weed species under limited moisture. Mesotrione and tembotrione plus atrazine provided efficacious POST control of the broadleaf weeds but poor fall panicum control. Topramezone plus atrazine controlled both fall panicum and broadleaf weeds. These findings highlight the importance of using mixtures of topramezone, mesotrione, and tembotrione with atrazine for broadleaf weed control, and topramezone and atrazine for both broadleaf weed and fall panicum control, particularly under limited moisture conditions that negatively affect the usefulness of pyroxasulfone. Although atrazine has reduced effectiveness when used PRE, these results suggest that it is still an important component when mixed with POST-applied topramezone, mesotrione, and tembotrione to provide effective control of problematic weed species in sweet corn on organic soils.

Acknowledgments. We thank the farm management and weed science group at the Everglades Research and Education Center for their assistance with establishing, maintaining, and collecting data from the experimental plots. This project was funded by the Specialty Crop Block Grant Program through the U.S. Department of Agriculture–Agricultural Marketing Service, and through the Florida Department of Agriculture Consumer Services, contract #26710. No conflicts of interest have been declared.

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