Weed Science 2016 64:531–539

Alternatives to Atrazine for Weed Management in Processing Sweet Corn

Zubeyde Filiz Arslan, Martin M. Williams II, Roger Becker, Vincent A. Fritz, R. Ed Peachey, and Tom L. Rabaey*

Atrazine has been the most widely used herbicide in North American processing sweet corn for decades; however, increased restrictions in recent years have reduced or eliminated atrazine use in certain production areas. The objective of this study was to identify the best stakeholder-derived weed management alternatives to atrazine in processing sweet corn. In field trials throughout the major production areas of processing sweet corn, including three states over 4 yr, 12 atrazine-free weed management treatments were compared to three standard atrazine-containing treatments and a weed-free check. Treatments varied with respect to herbicide mode of action, herbicide application timing, and interrow cultivation. All treatments included a PRE application of dimethenamid. No single weed species occurred across all sites; however, weeds observed in two or more sites included common lambsquarters, giant ragweed, morningglory species, velvetleaf, and wild-proso millet. Standard treatments containing both atrazine and mesotrione POST provided the most efficacious weed control among treatments and resulted in crop yields comparable to the weed-free check, thus demonstrating the value of atrazine in sweet corn production systems. Timely interrow cultivation in atrazine-free treatments did not consistently improve weed control. Only two atrazine-free treatments consistently resulted in weed control and crop yield comparable to standard treatments with atrazine POST: treatments with tembotrione POST either with or without interrow cultivation. Additional atrazine-free treatments with topramezone applied POST worked well in Oregon where small-seeded weed species were prevalent. This work demonstrates that certain atrazine-free weed management systems, based on input from the sweet corn growers and processors who would adopt this technology, are comparable in performance to standard atrazine-containing weed management systems.

Nomenclature: Atrazine; dimethenamid; mesotrione; tembotrione; common lambsquarters, *Chenopodium album* L.; giant ragweed, *Ambrosia trifida* L.; morningglory species, *Ipomea* spp.; velvetleaf, *Abutilon theoprasti* Medik.; wild-proso millet, *Panicum miliaceum* L.; sweet corn, *Zea mays* L.

Key words: Herbicide regulation, integrated weed management, North Central Region, Pacific Northwest, sweet corn industry.

Atrazine has been one of the most widely used herbicides in North American corn production because of its low cost, broad selectivity, and residual control of important weed species. No alternative herbicide has demonstrated economic and agronomic benefits equal to atrazine in field corn (Swanton et al. 2007). Because fewer herbicides are available for use in sweet corn compared to field corn, atrazine plays an even larger role in sweet corn production (Williams et al. 2010). However, growers' ability to use atrazine in sweet corn is decreasing. Several public water supplies in Illinois failed to meet water quality standards due to atrazine contamination (Illinois Environmental Protection Agency 2014). Minnesota has conducted extensive monitoring for atrazine in ground and surface waters because of numerous detections in stratified samplings since the 1990s (Minnesota Department of Agriculture 2015). Atrazine prohibition areas have increased in recent years in Wisconsin (Wisconsin Department of Agriculture, Trade, and Consumer Protection 2014). In western states, atrazine is commonly detected in rivers that carry protected species of salmon. Moreover, setbacks for atrazine application (e.g., wells, sink-

DOI: 10.1614/WS-D-16-00001.1

* First author: Weed Scientist, Düzce University, Düzce, Turkey, and Visiting Scholar, University of Illinois, Department of Crop Sciences, 1102 S. Goodwin Ave., Urbana, IL 61801; second author: Ecologist, USDA–Agricultural Research Service, Global Change and Photosynthesis Research, 1102 S. Goodwin Ave., Urbana, IL 61801; third author: Professor, University of Minnesota, Department of Agronomy and Plant Genetics, 411 Borlaug Hall, 1991 Upper Buford Circle, St. Paul, MN 55108; fourth author: Professor, University of Minnesota, Department of Horticultural Science, Southern Research and Outreach Center, 35838 120th Street, Waseca, MN 56093; fifth author: Associate Professor, Oregon State University, Department of Horticulture, 4017 Ag and Life Sciences Bldg., Corvallis, OR 97331; sixth author: Principal Scientist, General Mills Agricultural Research, 1201 N. 4th St., Le Sueur, MN 56058. Corresponding author's E-mail: martin.williams@ars.usda.gov

Table 1. Basic information about experimental sites, soil characteristics, hybrids, and dates of planting, herbicide applications, and harvest.

State	Site	Year	Latitude/ longitude	Dominant soil	Organic matter	Hybrid	Planting	PRE	POST	Harvest
					%					
Illinois	Dekalb	2013	41°55′46″N/	Catlin silt	5.8	DMC 2184	June 10	June 11	July 11	August 30
		2014	88°45′1″W	loam	4.4	GG 641	June 3	June 3	June 26	August 28
	Havana	2013	40°18′0″N/	Disco sandy	1.3	DMC 2184	May 15	May 15	June 7	July 31
		2014	90°3′39″W	loam	1.6	GG641	May 19	May 20	—[a]	—
	Urbana	2011	40°4′31″N/	Flanagan silt	3.4	Magnum II	May 19	May 19	June 8	August 4
		2012	88°14′31″W	loam	3.1	Magnum II	May 10	May 11	May 28	July 25
		2013			3.3	DMC 2184	May 20	May 20	June 17	August 8
		2014			2.9	GG 641	May 21	May 21	June 13	August 6
Minnesota	Le Sueur	2011	44°27′57″N/ 93°54′32″W	LeSueur clay loam	4.3	GG 641	June 9	June 11	June 28	August 24
	Waseca	2014	44°4′21″N/ 93°31′21″W	Webster clay loam	6.2	GG 641	May 29	May 29	June 26	September 3
Oregon	Corvallis	2013	44°34′15″N/ 123°16′34″W	Chehalis silty clay loam	2.4	Owatonna	June 12	June 13	July 4	September 12
	Lebanon	2013	44°32′11″N/ 122°54′25″W	Chapman loam	6.2	Owatonna	June 6	June 7	July 1	September 7

[a] Adverse weather interfered with POST application; therefore, site was abandoned.

holes, surface inlets, and perennial and intermittent streams) result in a patchwork of zones where atrazine cannot be applied within production fields such that it is becoming difficult to legally apply atrazine across an entire field. Nonetheless, a call for viable alternatives to atrazine in commercial sweet corn production has remained largely unanswered.

The United States leads sweet corn production globally. The majority of sweet corn acreage grown for processing, averaging 138,000 ha, is roughly split between the North Central Region (NCR) and Pacific Northwest (PNW). In the NCR, Illinois, Minnesota, and Wisconsin account for most of the processing sweet corn area, whereas Oregon and Washington account for a majority of the PNW area (NASS 2015). As such, robust weed management systems that perform well under a wide range of environmental conditions within a region, and preferably across regions, is desired.

Weed management systems used by sweet corn growers have been characterized in recent years. Interrow cultivation is used on < 50% of fields, atrazine use was higher in those fields without interrow cultivation, and 36% of fields received only a PRE herbicide application (Williams et al. 2010). Chloroacetamide herbicides, namely dimethenamid and *s*-metolachlor, have been the most widely used family of herbicides. In addition, inhibitors of the 4-hydroxyphenylpyruvatedioxygenase (HPPD), specifically mesotrione, tembotrione, and topramezone, have become widely used POST in sweet corn; however, most growers apply these products below the manufacturers' recommended rate and in combination with atrazine (Williams et al. 2010). Overall, atrazine accounts for 9% of total weed control cost in sweet corn production at an average total use rate of 1.35 kg ai ha^{-1}.

The objective of this study was to identify viable, stakeholder-derived alternatives to atrazine for weed management in processing sweet corn. To achieve this objective, a dozen atrazine-free weed management treatments were compared to three standard atrazine-containing treatments and a weed-free check. Atrazine-free treatments were developed based on input from the sweet corn processing industry. Therefore, this study represents an intersection of the tools available for weed management and strategies the sweet corn industry considers adoptable.

Materials and Methods

Twelve field studies were conducted in 4 yr from 2011 to 2014 at sites located in Illinois, Minnesota, and Oregon (Table 1). Sweet corn hybrid and production practices, including fertilizer application and insect pest management, were standard to each locale.

Experimental Approach. The experimental protocol was designed as a randomized complete block with four replications. Plots measured 3.0 m wide (4 rows on 76-cm row spacing) by 9.2 m long. Following several meetings with representatives of

https://doi.org/10.1614/WS-D-16-00001.1 Published online by Cambridge University Press

Table 2. Weed management systems tested in sweet corn between 2011 and 2014 in Illinois, Minnesota, and Oregon.

Group	Treatment[a]	Site of action[b]	Timing	Rate	Interrow cultivation	Total cost[c]
				g ai ha^{-1}		\$ ha^{-1}
Standard atrazine treatments	ATZ + DIM	5, 15	PRE	2,220 + 946	no	16.10
	ATZ + DIM fb ATZ + MES	5, 15, 5, 27	PRE fb POST	1,514 + 946 fb 505 + 105	no	25.80
	DIM fb ATZ + MES	15, 5, 27	PRE fb POST	946 fb 841 + 105	no	22.40
Atrazine-free treatments	DIM + TEM + THC	15, 27, 2	PRE	946 + 76 + 15	no	18.20
	DIM + SAF	15, 14	PRE	946 + 50	no	14.80
	DIM fb TOP	15, 27	PRE fb POST	946 fb 25	no	21.70
	DIM fb TEM	15, 27	PRE fb POST	946 fb 92	no	18.50
	DIM fb TOP + BEN	15, 27, 5	PRE fb POST	946 fb 25 + 1,121	no	29.90
	DIM fb TOP + NIC	15, 27, 2	PRE fb POST	946 fb 25 + 34	no	27.30
Atrazine-free treatments + cultivation	DIM + TEM + THC + CLT	15, 27, 2	PRE	946 + 76 + 15	yes	20.20
	DIM + SAF + CLT	15, 14	PRE	946 + 50	yes	16.90
	DIM fb TOP + CLT	15, 27	PRE fb POST	946 fb 25	yes	23.70
	DIM fb TEM + CLT	15, 27	PRE fb POST	946 fb 92	yes	20.50
	DIM fb TOP + BEN + CLT	15, 27, 5	PRE fb POST	946 fb 25 + 1,121	yes	31.90
	DIM fb TOP+NIC+CLT	15, 27, 2	PRE fb POST	946 fb 25+34	yes	29.30
Weed-free check	WF		PRE fb POST	946	yes	—

[a] Abbreviations: ATZ, atrazine; BEN, bentazon; CLT, cultivation; DIM, dimethenamid; fb, followed by; MES, mesotrione; NIC, nicosulfuron; SAF, saflufenacil; TEM, tembotrione, THC, thiencarbazone; TOP, topramezone.

[b] 2, acetolactate synthase inhibitor; 5, photosystem II inhibitor; 14, protoporphyrinigen oxidase inhibitor; 15, long chain fatty acid inhibitors; 27,4-hydroxyphenylpyruvate dioxygenase inhibitor.

[c] Herbicide costs from the 2014 Guide for Weed Management. University of Nebraska, Lincoln Extension, Lincoln, NE. Sprayer and cultivation costs from Estimated Costs of Crop Production in Iowa—2015. Iowa State University, Ames, IA. File A1-20, FM 1712, revised January 2015.

the Midwest Food Processors Association, a total of 16 treatments, including three standard atrazine-containing treatments, 12 atrazine-free treatments, and a weed-free check were chosen for testing (Table 2). Treatments varied with respect to herbicide mode of action, herbicide application timing, and interrow cultivation. All treatments included a PRE application of dimethenamid. Treatments reflected herbicides registered for use in sweet corn, except saflufenacil and tembotrione + thiencarbazone. Weed-free plots were handweeded as needed.

Prior to planting, seedbed preparation using conventional cultivation techniques controlled all previously emerged weeds. Preemergence herbicides were applied immediately after crop planting. Postemergence herbicides were applied when sweet corn was at the 3- to 4-collar growth stage. Herbicides were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 185 L ha^{-1} of spray volume at 275 kPa of pressure. Interrow cultivation treatments were made at the 4- to 5-collar growth stage using a low-residue cultivator equipped with 20-cm wide sweeps attached to parallel-linked C-shanks. Sweeps were operated at an average depth of 5 cm. Cost of herbicides (Anonymous 2014) and machinery operations (Anonymous 2015) were used to estimate treatment costs.

Data Collection. Visual estimates of weed control were recorded 2 wk after POST treatment (WAT) and at harvest, using a scale of 0 (no control) to 100 (complete control). All marketable ears were hand-picked near commercial maturity ($\sim$ 76% kernel moisture) from 6.1 m of the center two rows. Ears were considered marketable if they exceeded 4.5 cm in diameter, including husk leaves. Total number and mass of marketable ears were recorded. Number of ears per unit area was converted to boxes of ears based on 50 ears box^{-1}. Growing degree days (GDD) were determined using a base temperature of 10 C and daily temperature data from a nearby weather station. Irrigation was recorded and local rainfall data also were acquired.

Data Analysis. Two scales of inference were of interest in this research. First, performance of the treatments across the two production regions (NCR

https://doi.org/10.1614/WS-D-16-00001.1 Published online by Cambridge University Press

Table 3. For the time period from planting to harvest, cumulative water supply (rainfall + irrigation), cumulative growing degree days, and 30-yr means for each site year.

			Cumulative water supply		Cumulative growing degree days	
State	Site	Year	observed	30-yr	observed	30-yr
			———cm———		———°C———	
Illinois	Dekalb	2013	31.1	29.5	927	917
		2014	37.3	31.5	919	958
	Havana	2013	44.1	28.0	900	987
	Urbana	2011	28.2	27.7	1,119	947
		2012	25.7	27.7	1,064	881
		2013	34.3	28.5	972	990
		2014	50.2	27.5	964	957
Oregon	Corvallis	2013	25.9	6.3	936	807
	Lebanon	2013	29.2	8.4	1,048	933

and PNW) were examined. As such, data were pooled across all states and analyzed collectively. Secondly, to identify atrazine-free treatments that might have performed well locally, data were analyzed individually by state. With both approaches, ANOVA was conducted using a mixed effects model, where fields and replicates nested within fields were considered random effects, and treatments were considered fixed effects. Treatment differences were determined at $\alpha = 0.05$ level. Separation of least square means was performed using the protected LSD test. Analyses were conducted using JMP Pro 11 (SAS Institute Inc., Cary, NC).

Results and Discussion

Of the 12 field trials initiated from 2011 through 2014, three were canceled because of severe weather. Excessive rainfall at critical times reduced crop emergence, interfered with herbicide applications, and/or flooded the crop at Le Sueur, MN in 2011, Waseca, MN in 2014, and Havana, IL in 2014. Data from these sites, largely incomplete, were not included in the analysis and following discussion.

Over the course of the growing season, weather conditions reflected the wide range of environments in which processing sweet corn is grown in North America. Most trials experienced a water supply that was average to above average (Table 3). For instance, the wettest environment was Urbana in 2014 with 50.2 cm of rainfall between planting and harvest. Supplemental irrigation at most sites minimized the extent to which total water supply fell below the 30-yr average. The largest deviations from normal temperatures were in Urbana in 2011 and 2012, and both sites in Oregon. At these sites, GDDs accumulated from planting to harvest ranged from 114 to 183 GDDs above the 30-yr mean.

Nine predominant weed species were observed, including common cocklebur (*Xanthium strumarium* L.), common lambsquarters, common purslane (*Portulaca oleracea* L.), giant ragweed, hairy nightshade (*Solanum physalifolium* Rusby), morningglory species, pigweed species (*Amaranthus* spp.), velvetleaf, and wild-proso millet. No single weed species occurred across all sites; however, species observed in two or more sites included common lambsquarters, giant ragweed, morningglory species, velvetleaf, and wild-proso millet. These species are common in sweet corn. For instance, common lambsquarters and velvetleaf have been troublesome since the early 20th century, whereas wild-proso millet has become problematic in more recent decades (Williams et al. 2008). All sites in Illinois had one or more large-seeded broadleaf species; namely giant ragweed, morningglory species, and velvetleaf. In contrast, no large-seeded species were observed in Oregon, which was dominated by lambsquarters and wild-proso millet.

Weed Control. Averaged across all sites, standard treatments containing both atrazine and mesotrione POST provided season-long weed control of 95% (Table 4). Previous research has shown a synergistic interaction for weed control between atrazine and mesotrione applied POST (Abendroth et al. 2006; Sutton et al. 2002). Similarly, the addition of atrazine to tembotrione increased weed control 3 to 45% at 2 WAT and reduced variation of weed control by 45% in Illinois, Oregon, and Ontario (Williams et al. 2011a). Moreover, atrazine applied POST reduced risk of weak performance of other herbicides in sweet corn (Williams et al. 2011b).

Less than 70% weed control was observed in the standard atrazine treatment consisting of a single PRE application, a treatment common to ~ 16% of growers' fields (MM Williams, unpublished data). Although early-season weed control in the atrazine + dimethenamid (ATZ + DIM) treatment was comparable to other standard atrazine-containing treatments in Oregon, poor levels of weed control ($\leq$ 45%) were observed in Illinois at both sampling times. Triazine-resistant populations of common lambsquarters and velvetleaf have been observed throughout the NCR (Heap 2016). Moreover, dimethenamid is most effective on small-seeded species. These results make sense in light of the absence of large-seeded species in Oregon, yet

https://doi.org/10.1614/WS-D-16-00001.1 Published online by Cambridge University Press

Table 4. Overall weed control 2 WAT of POST herbicides and at harvest in response to three atrazine-containing standard treatments, six atrazine-free treatments, and six atrazine-free treatments plus interrow cultivation.[a]

	States					
	Illinois		Oregon		Mean	
Treatments[b]	2 WAT	Harvest	2 WAT	Harvest	2 WAT	Harvest
	% control					
ATZ + DIM	45 g	41 f	94 ab	90 b	70 f	65 f
ATZ + DIM fb ATZ + MES	94 ab	91 a	100 a	100 a	97 a	95 a
DIM fb ATZ + MES	95 a	91 a	99 a	100 a	97 a	95 a
DIM + TEM + THC	50 g	51 e	99 ab	99 a	74 f	75 ef
DIM + SAF	68 f	55 e	90 b	90 b	79 e	73 de
DIM fb TOP	74 def	78 bc	100 a	100 a	87 cde	89 b
DIM fb TEM	84 abcd	83 ab	99 a	100 a	92 abc	91 ab
DIM fb TOP + BEN	80 cde	78 bc	99 a	100 a	90 bcd	89 b
DIM fb TOP + NIC	82 cde	78 bc	99 a	98 a	91 abcd	88 b
DIM + TEM + THC + CLT	73 ef	67 d	100 a	98 ab	86 de	82 cd
DIM + SAF + CLT	78 cdef	70 cd	81 c	82 c	79 cde	76 c
DIM fb TOP + CLT	76 def	79 bc	100 a	100 a	88 bcde	90 ab
DIM fb TEM + CLT	88 abc	84 ab	100 a	99 a	94 ab	92 ab
DIM fb TOP + BEN + CLT	83 bcde	79 bc	100 a	100 a	92 abc	89 b
DIM fb TOP + NIC + CLT	84 abcd	80 b	100 a	100 a	92 abc	90 ab
Mean	77	74	97	97	87	85

[a] Means separation within columns using LSD comparison test at $\alpha = 0.05$.

[b] Abbreviations: ATZ, atrazine; BEN, bentazon; CLT, cultivation; DIM, dimethenamid; fb, followed by; MES, mesotrione; NIC, nicosulfuron; SAF, saflufenacil; TEM, tembotrione, THC, thiencarbazone; TOP, topramezone.

predominance of such species in Illinois, including several species that might carry alleles conferring resistance to atrazine.

Averaged across sites, several treatments containing tembotrione or topramezone POST were comparable in weed control to the standard treatments containing atrazine POST. Specifically, at-harvest weed control was > 90% for the dimethenamid followed by tembotrione (DIM fb TEM) treatment either with or without interrow cultivation (Table 4). Interrow cultivation also contributed to the dimethenamid followed by topramezone (DIM fb TOP + CLT) and dimethenamid followed by topramezone + nicosulfuron (DIM fb TOP + NIC + CLT) treatments having at-harvest weed control similar to the standard treatments containing atrazine POST. Moreover, regional differences in performance of atrazine alternative treatments were apparent. In Oregon, all treatments except those containing saflufenacil PRE were comparable in weed control to the atrazine standard treatments (Table 4). In contrast, only treatments containing tembotrione applied POST resulted in at-harvest weed control comparable to the atrazine standard treatments in Illinois. Differences in weed control between the states is due in large part to differences in observed species, as mentioned earlier, and their susceptibility to the herbicides used in this research.

Dimethenamid + tembotrione + thiencarbazone (DIM + TEM + THC) and dimethenamid + saflufenacil (DIM + SAF) were among the least effective treatments studied because of weed escapes in Illinois. For instance, at-harvest weed control in Illinois with DIM + TEM + THC or DIM + SAF was ≤ 55% (Table 4). Including interrow cultivation resulted in modest improvements in weed control (≤ 70%). These herbicides are not registered for use in sweet corn, but were of interest among the sweet corn processing industry. The poor performance of the DIM + TEM + THC and DIM + SAF treatments in Illinois, such as the ATZ + DIM standard, underscores the difficulty of relying heavily on PRE herbicides for control of the problematic large-seeded species that dominated Illinois sites.

Swanton et al. (2007) reported weed control with several PRE and POST field corn herbicides was reduced when atrazine was not part of the tank mix. Atrazine improved efficacy and reduced variation in weed control, especially for PRE treatments. Atrazine provides residual activity, unlike many herbicides available in sweet corn. The mean half-life of atrazine in soil is ~60 d, whereas that of most

https://doi.org/10.1614/WS-D-16-00001.1 Published online by Cambridge University Press

Table 5. Species-level weed control 2 WAT of POST herbicides and at harvest in response to three atrazine-containing standard treatments, six atrazine-free treatments, and six atrazine-free treatments plus interrow cultivation.[a]

Treatment[b]	Common lambsquarters 2 WAT	Common lambsquarters Harvest	Giant ragweed 2 WAT	Giant ragweed Harvest	Morningglory 2 WAT	Morningglory Harvest	Velvetleaf 2 WAT	Velvetleaf Harvest	Wild-proso millet 2 WAT	Wild-proso millet Harvest
	% control									
ATZ + DIM	80 e	61 g	49 d	39 e	46 fg	40 bc	45 j	35 h	51 e	45 e
ATZ + DIM fb ATZ + MES	100 a	98 a	98 ab	97 abc	91 a	79 a	99 ab	100 a	89 ab	82 abc
DIM fb ATZ + MES	100 a	97 ab	98 ab	98 a	92 a	79 a	99 a	99 a	89 ab	82 abc
DIM + TEM + THC	84 de	79 def	53 d	41 e	25 h	18 d	63 i	54 g	45 e	43 e
DIM + SAF	90 bcd	74 ef	72 c	61 d	80 ab	59 b	69 hi	59 g	44 e	44 e
DIM fb TOP	96 abc	89 abcd	93 ab	97 ab	25 h	15 d	84 ef	81 de	97 a	95 a
DIM fb TEM	100 a	94 abc	100 ab	100 a	54 def	43 bc	91 bcde	89 bcd	98 a	92 ab
DIM fb TOP + BEN	99 a	93 abc	98 ab	97 abc	50 efg	29 cd	94 abcd	90 abc	83 bc	75 cd
DIM fb TOP + NIC	90 cd	81 def	98 ab	99 a	63 cde	52 b	80 fg	75 ef	99 a	95 a
DIM + TEM + THC + CLT	92 abcd	77 def	87 b	82 bc	65 bcde	48 bc	75 gh	70 f	73 cd	58 de
DIM + SAF + CLT	89 cd	73 f	90 ab	82 c	73 bc	59 b	86 def	82 cde	67 d	55 e
DIM fb TOP + CLT	100 a	86 bcd	99 ab	99 a	35 gh	30 cd	90 cde	87 bcd	92 ab	92 abc
DIM fb TEM + CLT	100 a	88 abcd	100 a	98 a	68 bcd	52 b	95 abc	93 ab	95 ab	94 a
DIM fb TOP + BEN + CLT	98 ab	84 cde	100 a	100 a	55 def	43 bc	96 abc	92 ab	89 ab	77 bc
DIM fb TOP + NIC + CLT	96 abc	85 bcde	96 ab	99 a	67 bcde	54 b	88 cdef	82 cde	95 ab	89 abc
Mean	94	84	89	86	59	47	84	79	80	75

[a] Means separation within columns using LSD comparison test at $\alpha = 0.05$. Number of site years for each species: common lambsquarters (5), giant ragweed (2), morningglory (3), velvetleaf (6), wild-proso millet (4).

[b] Abbreviations: ATZ, atrazine; BEN, bentazon; CLT, cultivation; DIM, dimethenamid; fb, followed by; MES, mesotrione; NIC, nicosulfuron; SAF, saflufenacil; TEM, tembotrione, THC, thiencarbazone; TOP, topramezone.

other corn herbicides is < 30 d (Shaner 2014). One exception is topramezone, with a half-life of 125 d (Anonymous 2005). Dimethenamid is rapidly degraded in the soil with average half-life of 20 d (Shaner 2014).

Timely interrow cultivation did not consistently improve weed control in atrazine-free treatments, including when herbicides performed poorly. Fifty yr ago, mechanical weed control was a central part of weed management systems in sweet corn (Alex 1964), but today interrow cultivation is applied to less than one-half of growers' fields (Williams et al. 2010). In this study, interrow cultivation improved weed control in some treatments; however, it also stimulated emergence of morningglory species at certain sites (authors, personal observation). Previous research has shown that mechanical control must be applied shallowly and often, with intervals of ~ 18 d for effective morningglory control (Anonymous 1994). Whereas certain mechanical weed control methods increase spread of many perennial weed species (Gal et al. 2005), rotary cultivation can suppress field bindweed (*Convolvulus arvensis* L.), johnsongrass [*Sorghum halepense* (L.) Pers.], and purple nutsedge (*Cyperus rotundus* L.), in the interrow if applied in short, repeated intervals (Arslan and Uygur 2013).

Common lambsquarters is the most abundant broadleaf weed in sweet corn fields in the NCR (Williams et al. 2008) and was present in both sites at Oregon. Standard atrazine-containing treatments with mesotrione applied POST (e.g., ATZ + DIM fb ATZ + MES and DIM fb ATZ + MES) provided excellent control (≥ 97%) of common lambsquarters (Table 5). Treatments that relied on PRE herbicides alone failed to control common lambsquarters adequately, regardless of whether or not interrow cultivation was used. Others have shown that control of common lambsquarters with various PRE treatments alone is difficult (Chomas and Kells 2004; Spandl et al. 1997; Swanton et al. 2007). In contrast, the species was controlled >90% with DIM fb TEM treatment and the topramezone + bentazon (i.e., DIM fb TOP + BEN) treatment. These findings are consistent with Bollman et al. (2008) and Schönhammer et al. (2006) for field corn and sweet corn.

Giant ragweed, the seventh most abundant broadleaf species in sweet corn (Williams et al. 2008), was highly controlled by most treatments. At harvest, the only treatments not providing ≥ 97%

giant ragweed control included ATZ + DIM, DIM + TEM + THC, and DIM + SAF, regardless of interrow cultivation (Table 5). Soltani et al. (2011) also report poor giant ragweed control with DIM + SAF in field corn.

Standard treatments containing both atrazine and mesotrione POST provided the best control of morningglory species; however, control remained < 80% at harvest (Table 5). Vangessel et al. (2011) reported morningglory control in sweet corn ranged from 58 to 82% for metolachlor + atrazine + mesotrione and 74 to 86% for metolachlor followed by topramezone + atrazine. In the present work, the largest difference in topramezone vs. tembotrione, applied alone, was in morningglory control, where tembotrione was superior.

Velvetleaf is the second most abundant broadleaf species in sweet corn in the NCR (Williams et al. 2008). Excellent velvetleaf control was observed in the standard treatments containing both atrazine and mesotrione POST (Table 5). Postemergence treatments including DIM fb TOP + BEN or tembotrione and cultivation (i.e., DIM fb TEM + CLT) maintained velvetleaf control comparable to the standard treatments containing both atrazine and mesotrione POST. Results show the value of using multiple tactics for velvetleaf control.

Wild-proso millet infests one-half of processing sweet corn fields in the NCR (Williams et al. 2008) and was observed at the experimental sites in Oregon. By the time of sweet corn harvest, standard atrazine-containing treatments with mesotrione resulted in 82% control of wild-proso millet (Table 5). Atrazine-free treatments including topramezone, tembotrione, and topramezone + nicosulfuron POST controlled wild-proso millet $\geq$ 89% at harvest. The HPPD-inhibiting herbicides tembotrione and topramezone have become important herbicides for control of *Panicum* species in field corn (Schönhammer et al. 2006; Soltani et al. 2012).

Sweet Corn Yield. Weed-free yield across sites and states averaged 19.8 Mt ha^{-1}, or in terms of fresh market units, 1,116 boxes ha^{-1}. Historically, yields in the PNW are higher than yields in the NCR. Widespread use of irrigation, cool night-time temperatures, and an arid climate with abundant sunshine and low disease incidence in the PNW generally favors sweet corn production, relative to the NCR. For instance, average processing sweet corn yields are 18.1 and 22.4 Mt ha^{-1} in Illinois and Oregon, respectively (NASS 2015). Consistent with state-level production data, weed-free yields in the current research was 18.6 and 23.4 Mt ha^{-1} in Illinois and Oregon, respectively (Table 6).

Averaged across sites and states, most treatments resulted in sweet corn yields comparable to the weed-free check. Exceptions to this observation included one atrazine standard (i.e., ATZ + DIM) and both atrazine-free treatments with tembotrione and thiencarbazone (Table 6). These exceptions were due largely to the poor weed control of the ATZ + DIM treatment in Illinois and crop injury from both DIM + TEM + THC treatments in Oregon. Crop stunting in Oregon was 36% in the DIM + TEM + THC treatment, whereas injury was 22% in the same treatment with cultivation (data not shown). Crop injury was not observed at other locations; however, hybrid 'Owatonna' was used exclusively in Oregon sites. A mutation of a cytochrome P450 (CYP) allele in sweet corn is known to condition sensitivity to P450-metabolized herbicides from several modes of action, including acetolactate synthase (ALS)-inhibitors and HPPD-inhibitors applied POST (Nordby et al. 2008; Williams and Pataky 2010). As of 2010, mutant CYP alleles occurred in every major sweet corn breeding program in North America (Pataky et al. 2011). Because hybrid 'Owatonna' was not injured by POST application of tembotrione, sensitivity to the PRE treatment (i.e., DIM fb TEM + THC) might involve a different mechanism than previously reported for these two herbicide modes of action. From a practical standpoint, such injury would not affect present sweet corn production because the tembotrione + thiencarbazone combination currently is not registered for use on the crop.

Potential Alternatives to Atrazine. Atrazine remains one of the most effective and economical herbicides in North American corn production (Swanton et al. 2007; Williams et al. 2010). However, alternatives to atrazine have been needed for several years (Swanton et al. 2007; Williams et al. 2011b). Recent work by Recker et al. (2015) shows glyphosate and glyphosate-resistant crop traits have effectively become the alternative to atrazine in field corn in atrazine-prohibition areas of Wisconsin. Although a few glyphosate-resistant fresh market sweet corn hybrids are available, the vegetable processing industry has been reluctant to utilize transgenic crop technology (authors, personal observation), and glyphosate-resistant, processing sweet corn hybrids are not currently available (M Myers and S Grier, personal communications).

https://doi.org/10.1614/WS-D-16-00001.1 Published online by Cambridge University Press

Table 6. Yield of sweet corn in response to three atrazine-containing standard treatments, six atrazine-free treatments, and six atrazine-free treatments plus interrow cultivation.[a]

	State					
	Illinois		Oregon		Mean	
Treatments[b]	Ear no.	Ear mass	Ear no.	Ear mass	Ear no.	Ear mass
	boxes ha^{-1}	Mt ha^{-1}	boxes ha^{-1}	Mtha^{-1}	boxes ha^{-1}	Mt ha^{-1}
ATZ + DIM	986 d	16.0 c	1,050 a	22.3 abc	1,028 de	17.5 bcd
ATZ + DIM fb ATZ + MES	1,135 a	18.8 a	1,093 a	24.1 ab	1,134 ab	20.0 a
DIM fb ATZ + MES	1,080 abcd	18.5 a	1,060 a	23.2 abc	1,091 abcd	19.7 a
DIM + TEM + THC	1,017 cd	16.3 bc	495 b	10.4 d	979 e	15.5 d
DIM + SAF	1,055 abcd	17.3 abc	1,039 a	21.8 abc	1,072 abcd	18.5 abc
DIM fb TOP	1,029 bcd	17.1 abc	1,093 a	23.8 ab	1,088 abcd	18.8 abc
DIM fb TEM	1,134 a	19.3 a	1,071 a	23.2 abc	1,133 ab	20.3 a
DIM fb TOP + BEN	1,089 abc	18.0 abc	1,130 a	24.0 ab	1,124 abc	19.5 ab
DIM fb TOP + NIC	1,125 a	18.7 a	1,060 a	21.8 abc	1,138 a	19.5 ab
DIM + TEM + THC + CLT	1,079 abcd	17.7 abc	6,46 b	13.5 d	1,036 cde	17.1 cd
DIM + SAF + CLT	1,046 abcd	17.3 abc	996 a	21.6 bc	1,053 bcde	18.4 abc
DIM fb TOP + CLT	1,080 abcd	18.1 abc	1,082 a	23.3 abc	1,106 abcd	19.4 ab
DIM fb TEM + CLT	1,092 abc	18.2 ab	1,093 a	24.3 a	1,110 abcd	19.7 a
DIM fb TOP + BEN + CLT	1,085 abc	18.2 ab	996 a	22.1 abc	1,088 abcd	19.2 abc
DIM fb TOP + NIC + CLT	1,107 abc	18.3 ab	990 a	21.1 c	1,098 abcd	18.9 abc
Weed-free	1,119 ab	18.6 a	1,039 a	23.4 abc	1,116 abc	19.8 a
Mean	1,079	17.9	996	21.5	1,087	18.9

[a] Means separation within columns using LSD comparison test at $\alpha = 0.05$.

[b] Abbreviations: ATZ, atrazine; BEN, bentazon; CLT, cultivation; DIM, dimethenamid; fb, followed by; MES, mesotrione; NIC, nicosulfuron; SAF, saflufenacil; TEM, tembotrione, THC, thiencarbazone; TOP, topramezone.

In this work, standard treatments containing both atrazine and mesotrione POST provided the highest weed control and resulted in sweet corn yield comparable to the weed-free check across a range of diverse weed species and environments. Only two atrazine-free treatments consistently resulted in weed control and crop yield comparable to standard treatments with atrazine POST; specifically, the two treatments with tembotrione applied POST (i.e., DIM fb TEM and DIM fb TEM + CLT). Moreover, whether interrow cultivation was used or not, the treatments were comparable in cost to the atrazine-containing standards (Table 2). Additional atrazine-free treatments with topramezone applied POST worked well in Oregon, with weed control and crop yield comparable to the standard treatments with POST atrazine. Cost of the DIM fb TOP treatment was comparable to atrazine-standard treatments, although use of additional modes of action and interrow cultivation increased treatment costs at most by \$2.10 ha^{-1}. This work demonstrates that certain atrazine-free weed management systems, based on input from the sweet corn growers and processors who would adopt this technology, are comparable in performance to standard atrazine-containing weed management systems.

Acknowledgments

The authors greatly appreciate the technical support of Nick Hausman, Tom Hoverstand, Jim Moody, Charlie Rohwer and the crews at the University of Illinois and University of Minnesota. We thank TUBITAK (Scientific and Technological Council of Turkey) for supporting Z. F. Arslan. This material is based upon work that is supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture (number 2012-03266). Mention of a trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture and does not imply its approval to the exclusion of other products or vendors that also might be suitable.

Literature Cited

Abendroth JA, Martin AR, Roeth FW (2006) Plant response to combinations of mesotrione and photosystem II inhibitors. Weed Technol 20:267–274

Alex JF (1964) Weeds of tomato and corn fields in two regions of Ontario. Weed Res 4:308–318

Anonymous (1994) Weed Management for Developing Countries. FAO Plant Production and Protection Paper. Rome, Italy: Food and Agriculture Organization of the United Nations. 384 p

https://doi.org/10.1614/WS-D-16-00001.1 Published online by Cambridge University Press

Anonymous (2005) Memorandum for Topramezone. United States Environmental Protection Agency. http://www.epa.gov/pesticides/chem_search/cleared_reviews/csr_PC-123009_18-Mar-05_a.pdf. Accessed January 21, 2015

Anonymous (2014) 2014 Guide for Weed Management. Lincoln, NE: University of Nebraska, Lincoln Extension. 287 p

Anonymous (2015) Estimated Costs of Crop Production in Iowa—2015. File A1-20, FM 1712, revised January 2015. Ames, IA: Iowa State University. 13 p

Arslan ZF, Uygur FN (2013) Effect of some physical and mechanical weed control methods on some perennial weed species in tomato fields in Turkey. Page 178 *in* Proceedings of 16th EWRS Symposium. Samsun, Turkey: European Weed Research Society. [Abstract]

Bollman JD, Boerboom CM, Becker RL, Fritz VA (2008) Efficacy and tolerance to HPPD-inhibiting herbicides in sweet corn. Weed Technol 22:666–674

Chomas AJ, Kells JJ (2004) Triazine-resistant common lambsquarters (*Chenopodium album*) control in corn with pre-emergence herbicides. Weed Technol 18:551–554

Gal I, Pusztai P, Radics L (2005) Non-chemical weed management in carrot. Page 154 *in* Proceedings of 13th EWRS Symposium. Bari, Italy: European Weed Research Society. http://www.cabdirect.org/abstracts/20093146887.html?resultNumber=0&q=Non-chemical+weed+management+in+carrot. Accessed April 26, 2016

Heap I (2016) The International Survey of Herbicide Resistant Weeds. http://www.weedscience.org. Accessed February 24, 2016.

Illinois Environmental Protection Agency (2014) High Priority Public Water Supply TMDLs Impaired for Atrazine and Simazine. http://www.epa.illinois.gov/topics/water-quality/watershed-management/tmdls/atrazine-simazine/index. Accessed April 13, 2015

Minnesota Department of Agriculture (2015) Atrazine Information. http://www.mda.state.mn.us/chemicals/pesticides/atrazine.aspx-mon. Accessed May 4, 2015

[NASS] National Agricultural Statistics Service (2015) Vegetables 2014 Summary (January 2015). USDA–National Agricultural Statistics Service. http://www.nass.usda.gov/Statistics_by_Subject/index.php?sector=CROPS. Accessed March 19, 2015

Nordby JN, Williams MM II, Pataky JK, Riechers DE, Lutz JD (2008) A common genetic basis in the sweet corn inbred Cr1 for cross-sensitivity to multiple cytochrome P450-metabolized herbicides. Weed Sci 56:376–382

Pataky JK, Williams MM II, Headrick JM, Nankam C, du Toit LJ, Michener PM (2011) Observation from a quarter century of evaluating reactions of sweet corn hybrids in disease nurseries. Plant Dis 95:1492–1506

Recker RA, Mitchell PD, Stoltenberg DE, Lauer JG, Davis VM (2015) Late-season weed escape survey reveals discontinued atrazine use associated with greater abundance of broadleaf weeds. Weed Technol 29: 154–463

Schönhammer A, Freitag J, Koch H (2006) Topramazone—a new highly selective herbicide compound for control of warm season grasses and dicotyledoneous weeds in maize. J Plant Dis Prot 20:1023–1031

Shaner DL (2014) Herbicide Handbook. 10th edn. Lawrence, KS: Weed Science Society of America. 513 p

Soltani N, Kaastra AC, Swanton CJ, Sikkema PH (2012) Efficacy of topramezone and mesotrione for the control of annual grasses. Int Res J Agric Sci Soil Sci 2:46–50

Soltani N, Shropshire C, Sikkema PH (2011) Giant ragweed (*Ambrosia trifida* L.) control in corn. Can J Plant Sci 91:577–581

Spandl E, Rabaey TL, Kells JJ, Harvey RG (1997) Application timing for weed control in corn (*Zea mays*) with dicamba tank mixtures. Weed Technol 11:602–607

Sutton P, Richards C, Buren L, Glasgow L (2002) Activity of mesotrione on resistant weeds in maize. Pest Manag Sci 58:981–984

Swanton CJ, Gulden RH, Chandler K (2007) A rationale for atrazine stewardship in corn. Weed Sci 55:75–81

Vangessel M, Scott B, Johnson Q (2011) Does weed management for sweet corn differ with planting date? Page 101 *in* 2011 APS–IPPC Joint Meeting Abstracts of Presentations. Honolulu, HI: American Phytopathological Society. [Abstract]

Williams MM II, Boerboom CM, Rabaey TL (2010) Significance of atrazine in sweet corn weed management systems. Weed Technol 24:139–142

Williams MM II, Boydston RA, Peachey RE, Robinson D (2011a) Significance of atrazine as a tank-mix partner with tembotrione. Weed Technol 25:299–302

Williams MM II, Boydston RA, Peachey RE, Robinson D (2011b) Performance consistency of reduced atrazine use in sweet corn. Field Crop Res 121:96–104

Williams MM II, Pataky JK (2010) Factors affecting differential sensitivity of sweet corn to HPPD-inhibiting herbicides. Weed Sci 58:289–294

Williams MM II, Rabaey TL, Boerboom CM (2008) Residual weeds of sweet corn in the north central region. Weed Technol 22:646–653

Wisconsin Department of Agriculture, Trade, and Consumer Protection (2014) http://datcp.wi.gov/Environment/Water_Quality/Atrazine/index.aspx Accessed: April 13, 2015

Received January 5, 2016, and approved March 6, 2016.

Associate Editor for this paper: William Vencill, University of Georgia.