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Weed Management—Major Crops

Significance of Atrazine as a Tank-Mix Partner with Tembotrione

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Manufacturers of several POST corn herbicides recommend tank-mixing their herbicides with atrazine to improve performance; however, future regulatory changes may place greater restrictions on atrazine use and limit its availability to growers. Our research objectives were to quantify the effects of tank-mixing atrazine with tembotrione compared to tembotrione alone on (1) weed control, (2) variability in weed control, and (3) sweet corn yield components and yield variability. Field studies were conducted for 2 yr each in Illinois, Oregon, Washington, and Ontario, Canada. Tembotrione at 31 g ha^{-1} was applied alone and with atrazine at 370 g ha^{-1} POST at the four- to five-collar stage of corn. The predominant weed species observed in the experiment were common to corn production, including large crabgrass, wild-proso millet, common lambsquarters, and velvetleaf. For nearly every weed species and species group, the addition of atrazine improved tembotrione performance by increasing mean levels of weed control 3 to 45% at 2 wk after treatment. Adding atrazine reduced variation (i.e., standard deviation) in control of the weed community by 45%. Sweet corn ear number and ear mass were 9 and 13% higher, respectively, and less variable when atrazine was applied with tembotrione, compared to tembotrione alone. Additional restrictions or the complete loss of atrazine for use in corn will necessitate major changes in sweet corn weed management systems.

Nomenclature: Atrazine; tembotrione; common lambsquarters, *Chenopodium album* L.; large crabgrass, *Digitaria sanguinalis* (L.) Scop.; velvetleaf, *Abutilon theophrasti* Medik.; wild-proso millet, *Panicum miliaceum* L.; corn, *Zea mays* L.
Key words: HPPD inhibitor, regulatory, risk, weed control variability, yield variability.

Los fabricantes de varios herbicidas post-emergentes para el maíz recomiendan mezclarlos con atrazina para mejorar su eficacia; sin embargo, futuros cambios regulatorios quizá den lugar a mayores restricciones en el uso de atrazina y limite su disponibilidad para los agricultores. Los objetivos de esta investigación fueron cuantificar los efectos de mezclar atrazina con tembotrione comparado con el tembotrione aplicado solo en: 1) control de malezas, 2) la variabilidad en el control de malezas y 3) los componentes y variabilidad del rendimiento del maíz dulce. Durante dos años se llevaron a cabo estudios de campo, en Illinois, Oregon, Washington, y Ontario, Canadá. Se aplicó tembotrione solo a 31 g ha−1 y mezclado con atrazina a 370 g ha−1 en post-emergencia en la etapa de cuatro a cinco hojas del maíz. Las especies predominantes de maleza observadas en el experimento son comunes a la producción de maíz e incluyen *Digitaria sanguinalis*, *Panicum miliaceum, Chenopodium album* y *Abutilon theophrasti.* Para casi cada especie de maleza y grupo de especies, la adición de atrazina mejoró la eficacia del tembotrione, ya que incrementó los niveles medios de control de 3 a 45% a las dos semanas después de la aplicación. La adición de atrazina redujo la variación (desviación estándar) en el control de la comunidad de malezas en 45%. El número de mazorcas y el peso del maíz dulce fue 9 y 13% más alto, respectivamente, y hubo menor variabilidad cuando se aplicó atrazina con tembotrione, comparado con tembotrione aplicado solo. Mayores restricciones o la prohibición del uso de atrazina en el cultivo de maíz provocará la necesidad de un gran cambio en los sistemas de manejo de malezas en el maíz dulce.

Among the newest herbicides available for POST weed control in corn are inhibitors of 4-hydroxyphenylpyruvate dioxygenase (HPPD). These include mesotrione, topramezone, and tembotrione, which were registered for U.S. corn production in 2001, 2005, and 2007, respectively. Manufacturers recommend tank-mixing these herbicides with atrazine to improve product performance. Several researchers have observed greater, more consistent weed control when atrazine was tank-mixed with mesotrione (Abendroth et al. 2006; Sutton et al. 2002). However, controversy over atrazine's potential nontarget effects has led the U.S. Environmental Protection Agency to launch a comprehensive reevaluation of atrazine (EPA 2009). One possible outcome of the latest evaluation could be new restrictions on atrazine use.

Atrazine is one of the most widely used herbicides in corn. Nationwide, atrazine is applied to 66% of corn-producing hectares, although typically 80% or more of corn-producing hectares in the Midwest receive atrazine applications (NASS 2005). Approximately 32 million kilograms of atrazine are applied annually in the United States (EPA 2009). Atrazine's popularity among growers is largely due to its low cost and highly efficacious residual control of many problematic weeds. Atrazine plays an even larger role in commercial production of specialty types of corn, such as sweet corn, because fewer herbicides are registered for use and there are few hybrids resistant to nonselective herbicides (e.g., glufosinate and glyphosate). Sweet corn growers apply HPPD-inhibiting herbicides below the manufacturer's recommended rate in most fields in the Midwest (Williams et al. 2010). Despite

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extensive use of atrazine and HPPD-inhibiting herbicides in sweet corn, over one-half of fields suffer yield loss due to weeds (Williams et al. 2008).

The objectives of the research were to quantify the effects of tank-mixing atrazine with tembotrione compared to tembotrione alone on (1) weed control, (2) variability in weed control, and (3) crop yield components and yield variability. The research was conducted in the major production areas where sweet corn is grown for processing in North America.

Materials and Methods

Experimental Methodology. Between 2007 and 2009, field studies were conducted for 2 yr at each of the following locations: Urbana, IL; Corvallis, OR; Prosser, WA, and Ridgetown, ON, Canada. Two sugary sweet corn hybrids, 'Quickie'[2] and 'Code128',[3] were planted into a tilled seedbed in May (May 5 to May 28). Sweet corn was grown using standard fertility and irrigation production practices to achieve yields representative of each location (Anonymous 2003, 2006). Naturally occurring weed populations were used. The experimental design was a randomized complete block with four to six replications at each location. Plot size was four 0.76-m-spaced rows by 9.1 m. Treatments included 31 g ha^{-1} of tembotrione[1] applied POST (one-third of the labeled rate) without atrazine (−) and with atrazine (+) at 370 g ha^{-1}. A season-long weed-free treatment was included. POST treatments were applied to sweet corn with four or five visible leaf collars, approximately 1 mo after planting. Applications included 1% v/v crop oil concentrate and 2.5% v/v urea ammonium nitrate (28% nitrogen) in 187 L ha^{-1} of spray volume. Size of weed populations at the time of treatment application ranged widely, though three-leaf grasses and five-leaf broadleaves were common to most site-years. The season-long weed-free treatment was maintained by a PRE application of 1.7 kg ha^{-1} of atrazine plus 1.8 kg ha^{-1} of metolachlor and weekly hand-weeding as needed.

Percentage of weed control was visually rated on a scale of 0 = no control to 100 = complete control for individual species, species groups (e.g., all grasses), and overall weed community. Ratings were made 2 wk after treatment (WAT) and at the time of sweet corn harvest. Harvest of Quickie and Code128 averaged 6.7 and 9.3 WAT, respectively. Marketable sweet corn ears, measuring $\geq$ 4.5 cm in diameter with husks, were hand-harvested from the two center rows over 6.0 m of row, and ear mass and number were recorded. For each location, ear mass and number in each treatment were divided by that in the weed-free check to determine relative ear mass and relative ear number.

Statistical Analysis. If a weed species occurred at multiple sites or years, responses were combined for analysis. The means and variances of percentage of weed control were calculated for atrazine treatments at 2 WAT and at harvest for each species and species group. The equality of means between $\pm$ atrazine treatments were tested using one-tailed paired *t*-tests for weed species and yields. Equality of variances between $\pm$ atrazine treatments were tested using one-tailed tests of the *F* distribution.

Results and Discussion

Weed species observed in this study are common to commercial corn production (Gibson et al. 2005; Kruger et al. 2009). Predominant grasses included barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], large crabgrass [*Digitaria sanguinalis* (L.) Scop.], wild-proso millet (*Panicum miliaceum* L.), and witchgrass (*Panicum capillare* L.). Of 56 weed species observed in commercial sweet corn production in the Midwest, wild-proso millet, large crabgrass, and barnyardgrass ranked among the nine most abundant grasses (Williams et al. 2008). Predominant broadleaf species included common lambsquarters (*Chenopodium album* L.) and velvetleaf (*Abutilon theophrasti* Medik.), the first and second most abundant broadleaf weeds observed in Midwest sweet corn fields (Williams et al. 2008). Powell amaranth (*Amaranthus powellii* S. Wats.) and redroot pigweed (*Amaranthus retroflexus* L.) were the predominant pigweed species (e.g., *Amaranthus* sp.), the third most abundant broadleaf observed in grower's fields (Williams et al. 2008). Redroot pigweed was observed in most sites; however, Powell amaranth was observed only in Oregon. Predominant nightshades (e.g., *Solanum* sp.) were hairy nightshade (*Solanum physalifolium* Rusby) in Oregon and Washington, and eastern black nightshade (*Solanum ptychanthum* Dunal) in Illinois and Ontario. Eastern black nightshade was the fourth most abundant broadleaf weed in Midwest sweet corn fields (Williams et al. 2008). In addition, common purslane (*Portulaca oleracea* L.) was observed in most sites, the eighth most abundant broadleaf weed observed in grower's fields (Williams et al. 2008).

At 2 WAT, the addition of atrazine increased weed control of every species and weed group except witchgrass (Table 1). Tembotrione alone at 2 WAT provided $>$ 95% control of only eastern black nightshade, Powell amaranth, and velvetleaf. Similar trends were observed at the harvest rating; the addition of atrazine to tembotrione increased control of 8 of 11 species, and improved control of all combined weed groups.

The addition of atrazine to tembotrione reduced variability in weed control responses. Variability in weed control (variance) is described by the standard deviation. For example, the standard deviation of wild-proso millet control at harvest was 23% for tembotrione alone, but only 4% for tembotrione + atrazine (Table 1). Variability was reduced by the addition of atrazine for 9 of 11 species at 2 WAT and at harvest. The three species where variability was not reduced for at least one rating time were barnyardgrass, large crabgrass, and witchgrass. When the entire weed community was considered, the addition of atrazine reduced the standard deviation 63% at 2 WAT and 45% at harvest.

Improved weed control with the addition of atrazine to tembotrione increased the number of marketable ears 9%, and marketable ear mass 13% compared to tembotrione alone (Table 2). Mean ear number and ear mass were within 3% of the weed-free yields with tembotrione + atrazine. When tembotrione was applied alone, mean ear number fell 13% and ear mass fell 17% compared to weed-free yields. Relative sweet corn ear number and ear mass were less variable with the addition of atrazine; only 15% compared to 28 to 31% with tembotrione alone.

Table 1. Percentage of weed control (mean and standard deviation) in sweet corn treated POST with tembotrione, without (−) or with (+) atrazine, assessed 2 wk after treatment (2 WAT) and at crop harvest. Eight field sites were located in Corvallis, OR; Prosser, WA; Ridgetown, ON, Canada; and Urbana, IL, in 2007 to 2009.

		Mean				Standard deviation			
		2 WAT		Harvest		2 WAT		Harvest	
Species or group	N[a]	−	+	−	+	−	+	−	+
		% control[b]							
Barnyardgrass	20	68	*89	66	*91	13	9	22	*10
Large crabgrass	10	86	*98	75	75	15	*3	23	21
Wild-proso millet	10	94	*99	74	*96	6	*2	23	*4
Witchgrass	24	70	79	93	92	45	38	13	12
Common lambsquarters	48	81	*95	78	*94	20	*8	23	*11
Common purslane	44	50	*95	76	*96	29	*7	31	*6
Eastern black nightshade	20	96	*100	81	*100	8	*0	24	*1
Hairy nightshade	34	91	*100	83	*100	12	*0	25	*1
Powell amaranth	24	96	*100	94	99	10	*0	20	*1
Redroot pigweed	46	80	*95	61	*85	30	*13	37	*25
Velvetleaf	20	97	*100	91	*98	5	*1	12	*3
All nightshades	64	93	*100	82	*99	11	*1	25	*4
All pigweeds	70	86	*97	72	*90	26	*10	36	*21
All grasses	80	78	*88	79	*88	27	*22	21	*14
All broadleaves	80	80	*97	75	*93	17	*7	25	*14
Weed community	80	77	*95	74	*91	16	*6	20	*11

[a] Number of pairs of ± atrazine treatment observations.

[b] Asterisk (*) denotes means or variances (reported as standard deviations) are not equal between ± atrazine ($P \leq 0.05$).

Atrazine tank-mixed with tembotrione reduced the risk of herbicide failure and yield losses. The addition of atrazine (370 g ha^{-1}) to tembotrione (31 g ha^{-1}) improved control of individual species by 5 to 45%. Control of the entire weed community improved from an unacceptable level (77%), to an acceptable level (95%) with atrazine. Furthermore, atrazine reduced variability in weed control responses, meaning that weed control of most species and groups was more consistent when atrazine was included. One would expect a similar trend with less improvement in agronomic benefits from atrazine at higher tembotrione rates; however, these data reflect the current use of reduced rates of HPPD-inhibiting herbicides in sweet corn (Williams et al. 2010). Although mesotrione and topramezone were not tested, similar weed control benefits to tank-mixed atrazine are likely. The labeled rate of topramezone provides suboptimal weed control in some conditions; however, addition of atrazine improves consistency of weed control with topramezone (Boydston and Peachey, personal communication). Others have shown addition of atrazine to mesotrione resulted in greater, more consistent weed control in field corn (Armel et al. 2009; Johnson et al. 2002).

Table 2. Yield of sweet corn (mean and standard deviation) treated POST with tembotrione, without (−) or with (+) atrazine. Eight field sites were located in Corvallis, OR; Prosser, WA; Ridgetown, ON, Canada; and Urbana, IL, in 2007 to 2009.

	Mean		Standard deviation	
Yield variable[a]	−	+	−	+
	boxes ha^{-1}[b]			
Ear number	942	*1,030[c]	441	*355
	kg ha^{-1}			
Ear mass	16,400	*18,600	9,300	8,000
	% of weed-free			
Relative ear number	87	*100	28	*15
Relative ear mass	83	*97	31	*15

[a] Number of pairs of ± atrazine treatment observations equal 80.

[b] Fifty ears per box.

[c] Asterisk (*) denotes means or variances (reported as standard deviations) are not equal between ± atrazine ($P \leq 0.05$).

These data provide further evidence of the importance of atrazine to sweet corn production. Our observations of the increased level of weed control, more consistent weed control, and yield protection provided when atrazine is tank-mixed with another herbicide helps partially explain why atrazine is popular among corn growers. Gunsolus and Buhler (1999) argue the main value of herbicides is their ability to reduce yield variability. Atrazine accounts for ≤ 9% of total weed management costs in sweet corn (Williams et al. 2010) and is viewed by many as an inexpensive tool for growers to improve weed control of several herbicides. No other herbicide currently available provides comparable economic and agronomic attributes to atrazine for its crop safety, compatibility with other herbicides, and complementary weed control spectrum (Swanton et al. 2007). Additional restrictions or the complete loss of atrazine for use in corn will necessitate major changes in sweet corn weed management systems.

Sources of Materials

[1] Laudis™ herbicide, Bayer CropScience LP, Research Triangle Park, NC.

[2] Quickie hybrid, Crookham Company, Caldwell, ID.

[3] Code128 hybrid, General Mills, LeSueur, MN.

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Literature Cited

Abendroth, J. A., A. R. Martin, and F. W. Roeth. 2006. Plant response to combinations of mesotrione and photosystem II inhibitors. Weed Technol. 20:267–274.

Anonymous. 2003. Sweet Corn Pest Management Strategic Plan. http://pestdata.ncsu.edu/pmsp/pdf/NCSweetcorn.pdf. Accessed: 29 January 2004.

Anonymous. 2006. Vegetables 2005 Summary. Washington, DC: U.S. Government Printing Office. Pp. 17–69.

Armel, G. R., R. J. Richardson, H. P. Wilson, and T. E. Hines. 2009. Strategies for control of horseweed (*Conyza canadensis*) and other winter annual weeds in no-till corn. Weed Technol. 23:379–383.

[EPA] Environmental Protection Agency. 2009. Atrazine Science Reevaluation: Potential Health Impacts. EPA-HQ-OPP-2009-0759-0003. http://www.epa.gov/pesticides/reregistration/atrazine/atrazine_update.htm. Accessed: 27 October 2009.

Gibson, K. D., W. G. Johnson, and D. E. Hillger. 2005. Farmer perceptions of problematic corn and soybean weeds of Indiana. Weed Technol. 19:1065–1070.

Gunsolus, J. L. and D. D. Buhler. 1999. A risk management perspective on integrated weed management. Pages 167–187 *in* D. D. Buhler, ed. Expanding the Context of Weed Management. New York: Food Products.

Johnson, B. C., B. G. Young, and J. L. Matthews. 2002. Effect of postemergence application rate and timing of mesotrione on corn (*Zea mays*) response and weed control. Weed Technol. 16:414–420.

Kruger, G. R., W. G. Johnson, and S. C. Weller, et al. 2009. U.S. grower views on problematic weeds and changes in weed pressure in glyphosate-resistant corn, cotton, and soybean cropping systems. Weed Technol. 23:162–166.

[NASS] National Agricultural Statistics Service. 2005. Agricultural Chemical Use Database. http://www.pestmanagement.info/nass/app_usage.cfm. Accessed: 3 June 2010.

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

Swanton, C. J., R. H. Gulden, and K. Chandler. 2007. A rationale for atrazine stewardship in corn. Weed Sci. 55:75–81.

Williams, M. M. II, C. M. Boerboom, and T. L. Rabaey. 2010. Significance of atrazine in sweet corn weed management systems. Weed Technol. 24:139–142.

Williams, M. M. II, T. L. Rabaey, and C. M. Boerboom. 2008. Residual weeds of sweet corn in the north central region. Weed Technol. 22:646–653.

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