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Significance of Atrazine in Sweet Corn Weed Management Systems

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Weed management systems used by sweet corn growers, including the role of atrazine, are poorly characterized. Management records of 175 fields throughout the major sweet corn production areas of the Midwest were surveyed from 2005 to 2007. Seventy-four percent of sweet corn fields in the Midwest were grown in rotation with soybean or corn. Interrow cultivation was used on 48% of fields, and atrazine use was higher in those fields without interrow cultivation. A majority of fields (54%) received both PRE and POST herbicide applications. Mesotrione was applied below the registered use rate in two-thirds of the fields in which it was used POST. Atrazine rates in sweet corn were highest when the preceding crops were other vegetables, compared to preceding crops of soybean or corn. Selective herbicides are used extensively in U.S. sweet corn production, accounting for 94% of total weed management expenditures which average $123/ha. Growers treated 66% of fields with one or more applications of atrazine at an average total use rate of 1.35 kg ai/ha. The estimated annual net cost to replace atrazine in U.S. sweet corn production with the broad spectrum broadleaf herbicide, mesotrione, is $9.2 million.

Nomenclature: Atrazine; mesotrione; corn, *Zea mays* L.; soybean, *Glycine max* (L.) Merr.

Key words: Economics, integrated weed management, reduced rate, regulatory, survey.

Ha sido insuficiente la investigación llevada al cabo en cuanto a los sistemas de manejo de malezas utilizados por los productores de maíz dulce incluyendo el papel que ha jugado el uso de la atrazine en ellos. Los registros de manejo de malezas de 175 parcelas se revisaron en las áreas de mayor producción de maíz dulce localizadas en el medio oeste del 2005 al 2007. El 74% de las parcelas fueron sembradas en rotación con soya o maíz forrajero. Se utilizó el cultivo entre surcos en el 48% de las parcelas y el uso de atrazine fue mayor en las parcelas donde no se sembró entre surcos. La mayoría de las parcelas (54%) recibió aplicaciones de herbicidas tanto en el período de pre-siembra como el de post-siembra. El mesotrione fue aplicado por debajo de la dosis registrada en dos terceras partes de las parcelas en donde se usó éste en post-siembra. Las dosis utilizadas de atrazine en maíz dulce fueron más altas cuando el cultivo precedente fue otro vegetal en comparación a cuando el cultivo anterior fue soya o maíz forrajero. Los herbicidas selectivos son usados frecuentemente en la producción de maíz dulce en los Estados Unidos y representan el 94% del total de los gastos efectuados en el manejo de malezas, cuyo promedio es de $ 123.00 dólares por Ha. Los productores trataron el 66% de sus parcelas con una o más aplicaciones de atrazine con una dosis promedio de 1.35 Kg de ingrediente activo (ia) x Ha. El costo neto anual estimado para reemplazar el atrazine en la producción de maíz dulce en los Estados Unidos con el mesotrione, que es un herbicida de amplio espectro para hoja ancha, es de $9.2 millones de dólares.

Atrazine has been registered for use in U.S. crop production for over 50 yr. A triazine herbicide, atrazine can be applied PRE and POST to control many broadleaf and some grass weed species. It is primarily used on sorghum [*Sorghum bicolor* (L.) Moench], sugarcane (*Saccharum* L.), and all types of corn. In 2006 the U.S. Environmental Protection Agency (EPA) issued a cumulative risk assessment of atrazine and completed the reregistration eligibility process for the herbicide. However, controversy remains over the use of atrazine with regard to animal toxicology and human epidemiology. Consequently, EPA has launched a comprehensive reevaluation of human health and ecological risk assessments associated with atrazine (EPA 2009). Based on the outcomes of this latest evaluation, EPA will decide whether to revise its current atrazine risk assessments and if new restrictions are necessary.

Despite five decades of developments in weed control technology since atrazine was first registered, atrazine remains one of the most widely used herbicides in North America. Because atrazine provides low-cost, highly efficacious residual control of many problematic weeds in the cornbelt, it continues to be a central component of weed management systems in field corn. In the United States alone, approximately 32 million kg of active ingredient are applied annually, with the highest use of atrazine in the Midwest (EPA 2009). Swanton et al. (2007) found no other herbicide had economic and agronomic benefits equal to atrazine in field corn. The economic impact of a ban of atrazine in all types of corn almost certainly would drive up production costs as growers strive to maintain current levels of weed control.

Sweet corn annual production area is 258,000 ha, which accounts for less than 1% of the total area of corn production in the United States. Sweet corn is one of the most popular vegetable crops and has a farm value of approximately $900 million (NASS 2008). Sweet corn has benefited from some weed management tactics developed for use in field corn. For instance, more herbicides are registered for use in sweet corn than most minor crops. Unlike field corn, hybrid sensitivity to certain herbicides has limited their use in sweet corn. In addition, nonselective herbicides can only be used with herbicide-resistant hybrids (e.g., glyphosate-resistant). Weeds continue to cause significant losses in yield and quality in most fields (Williams et al. 2008).

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Table 1. Nonchemical weed management tactics used in sweet corn fields from survey of management records in Illinois, Minnesota, and Wisconsin from 2005 to 2007.

Tactic	Number of fields[a]	Variable	Percent of fields
Crop rotation	121	soybean	36
		sweet corn	19
		peas	15
		field corn	13
		seed corn	6
		wheat	5
		cabbage	3
		lima bean	2
		snap bean	1
Row spacing	175	76 cm	94
		56 cm	6
Mechanical	174	preplant cultivation	99
		interrow cultivation	48

[a] Number of fields reporting each tactic.

Table 2. Herbicide use in sweet corn fields from survey of management records in Illinois, Minnesota, and Wisconsin from 2005 to 2007 ($n = 173$).

Application type	Herbicide	Average herbicide use rate	Percent of fields
		kg ai/ha[a]	
PRE only		—	36
POST only		—	10
PRE + POST		—	54
PRE	metolachlor	1.80	52
	atrazine	1.49	43
	dimethenamid-P	1.03	33
	alachlor	2.20	5
	mesotrione	0.21	5
	simazine	0.75	2
POST	atrazine	0.690	35
	mesotrione	0.086	26
	bentazon	0.810	21
	nicosulfuron	0.033	12
	carfentrazone	0.009	8
	topramezone	0.015	5
	2,4-D	0.540[a]	1
PRE, POST,	atrazine	—	66
PRE + POST	mesotrione	—	31

[a] Herbicide rate expressed in kg ae/ha.

The weed management tactics being used in sweet corn, and the extent to which production relies on atrazine, has not been aggregated and made public. In order to assess the current status of weed management systems, we surveyed field records throughout the major sweet corn production areas of the Midwest. The objectives of this study were (1) to characterize weed management currently being used in sweet corn, and (2) to document the role of atrazine in these systems.

Materials and Methods

Field surveys of the weed communities observed near the time of sweet corn harvest were conducted using previous research (Williams et al. 2008). In brief, fields were drawn randomly from weekly lists of fields scheduled by collaborators for harvest. The 175 surveyed fields represented a range of harvest times (July through early October) within Illinois, Minnesota, and Wisconsin from 2005 to 2007. Information about the agronomic and weed management practices used in those fields was obtained from the collaborators and complete details were reported by Williams et al. (2009). For purposes of the present work, the survey data were analyzed for information on previous crop, sweet corn row spacing, planting date, tillage practices, and details on herbicide application (products, rates, and application dates). Based on interrow cultivation and herbicide use in each field, weed management expenditures were calculated using costs of herbicides (Boerboom et al. 2008) and machinery costs for herbicide applications and tillage practices (University of Minnesota Extension 2008). Herbicide application costs might have been underestimated because custom application costs are higher than grower application costs.

Weed management tactics were characterized as a percentage of use in surveyed fields. Two hypotheses were tested with the chi-square test for independence: (1) total atrazine use was more frequent in fields without interrow cultivation compared to interrow cultivated fields; and (2) POST-atrazine use was more frequent when other POST herbicides were applied below the registered use rate (hereafter called ‘‘reduced rate’’). Pearson correlations between atrazine use and sweet corn planting date were conducted. Probability values for correlation were calculated using the Bonferroni correction for multiple parameters (Neter et al. 1996). Due to lack of normality in the following datasets, two hypotheses were tested with the Kolmogorov–Smirnov test of frequency distributions: (1) in fields receiving a single herbicide application (i.e., PRE only or POST only), atrazine use rates were similar to fields receiving multiple herbicide applications (i.e., both PRE and POST); and (2) atrazine use in sweet corn was comparable across all the different types of previous crops. Analyses were conducted in SYSTAT 11.0[1] and all hypotheses were tested at $\alpha = 0.05$.

Results and Discussion

Weed Management Systems. Several weed management tactics were used in sweet corn, including crop rotation, row spacing, mechanical control, and PRE and POST herbicides. Of the 121 fields for which the previous crop was reported, 38% of fields were following some type of corn, either field corn, seed corn, or sweet corn (Table 1). Soybean was the previous crop on 36% of surveyed fields, and 21% of fields had been planted to peas (*Pisum sativum* L.), lima bean (*Phaseolus lunatus* L.), snap bean (*Phaseolus vulgaris* L.), or cabbage (*Brassica oleracea* L.) (hereafter called ‘‘vegetables’’). Peas are the most frequent previous vegetable crop because sweet corn can be double-cropped after an early pea harvest. Overall, the majority of sweet corn in the Midwest is grown in rotation with soybean or corn.

Sweet corn was commonly planted in rows spaced 76 cm apart into a tilled seedbed. Preplant tillage was reported on all but one of 174 fields (Table 1). Preplant tillage was used widely in sweet corn to reduce early-season weed interference and is consistent with a previous report (Anonymous 2003). Ninety-four percent of fields were planted in sweet corn rows spaced 76-cm apart, and six percent of production fields had a

56-cm row spacing. Narrow row sweet corn was observed on farms in Minnesota growing sugarbeet (*Beta vulgaris* L.), where growers have ready access to narrow row equipment. Interrow cultivation was used on 48% of all fields.

Every field was treated with one or more applications of herbicides. A majority of fields (54%) received both PRE and POST herbicide applications (Table 2). Use of only PRE herbicides (36%) was more common than use of only POST herbicides (10%). No field received more than a single POST application. The most commonly applied PRE herbicides were metolachlor (52%), atrazine (43%), and dimethenamid-P (33%). The most commonly applied POST herbicides were atrazine (35%), mesotrione (26%), and bentazon (21%).

This study sheds some light on the extent to which growers were willing to assume risk and apply herbicides below registered use rates. Mesotrione, nicosulfuron, and topramezone each have a single registered POST use rate; therefore, we were able to quantify how frequently growers applied these herbicides at a reduced rate. Nicosulfuron use rate was reduced in only one of the 21 fields where the herbicide was applied. Topramezone use was reduced (as much as 40%) in four of nine fields. Reduced topramazone rates might have been used in some fields because rotations to soybean and snap bean were permitted only after a reduced rate. In contrast, mesotrione use was reduced (as much as 84%) in 30 of the 45 fields where it was applied, but the mean use rate was still 82% of the labeled POST rate. Previous research has shown a synergistic interaction for weed control between atrazine and reduced rates of mesotrione applied POST (Abendroth et al. 2006; Sutton et al. 2002). In the present research, there was no association between reduced use rates of POST mesotrione and POST atrazine use (n = 45, Chi-square = 4.680, P = 0.197), indicating growers were not necessarily using atrazine more frequently when they applied mesotrione at reduced rates POST.

Estimated expenditures on total weed management ranged from $39/ha to $196/ha, averaging $123/ha across the region (data not shown). Cost of herbicides and their applications accounted for an average of 94% of weed management expenditures, with interrow cultivation accounting for the balance.

Atrazine Use. Considering both PRE and POST applications, atrazine was applied to 66% of fields, making it the most widely used herbicide in sweet corn. On fields where atrazine was used, it was applied at an average rate of 1.35 kg/ha, with higher use rates PRE (1.49 kg/ha) compared to POST (0.69 kg/ha). Compared to fields receiving both PRE and POST herbicides, use rate of atrazine PRE was 24% lower in those fields without POST herbicide applications (n = 74, K–S test = 0.412, P = 0.003). A similar relationship was observed for atrazine applied POST. Compared to fields receiving both PRE and POST herbicides, POST use rate of atrazine was 9% lower in those fields without PRE herbicide applications (n = 60, K–S test = 0.469, P = 0.015). Therefore, in fields receiving a single herbicide application (PRE only or POST only), atrazine use rates were lower than in fields receiving multiple herbicide applications (both PRE and POST). These findings suggest that growers who use more atrazine, and make an additional herbicide application, are on fields with higher weed infestations.

Sweet corn is planted from early April to early July in the upper Midwest. Total atrazine use was constant across planting dates of the fields surveyed in this work (data not shown). However, a negative association (n = 60, Pearson correlation = −0.385, P = 0.002) between crop planting date and POST atrazine use rate was observed. Atrazine POST use rate might be related to level of weed infestation. Weed emergence typically declines with later planting dates. This pattern likely occurred in sweet corn because weed interference declined in September-harvested fields, relative to August-harvested fields (Williams et al. 2008). Over the course of the planting season, sweet corn competitive ability against redroot pigweed (*Amaranthus retroflexus* L.), common lambsquarters (*Chenopodium album* L.), and large crabgrass [*Digitaria sanguinalis* (L.) Scop.] improved in mid-June and early-July plantings as compared to April and May plantings (Williams 2009).

Interrow cultivation influenced atrazine use in surveyed fields. In the absence of interrow cultivation, atrazine was used more frequently (n = 173, Chi-square = 16.6, P < 0.001). Of the 90 fields that were not interrow cultivated, 80% received an atrazine application, whereas of the 83 fields that were interrow cultivated, 51% received an atrazine application. Growers appeared to rely more on supplemental mechanical weed control when atrazine was not used.

Total atrazine used in sweet corn varied with the crop grown the previous year. Atrazine use in sweet corn was higher (mean = 1.08 kg/ha) when the preceding crops were vegetables, compared to when the preceding crops were all types of corn (mean = 0.90 kg/ha) (n = 59, K–S test = 0.615, P < 0.001). Atrazine use in sweet corn was lower (mean = 0.72 kg/ha) when the preceding crop was soybean, compared to when the preceding crops were all types of corn (n = 74, K–S test = 0.663, P < 0.001). Relative to agronomic crops, fewer herbicides are registered for use in snap bean, lima bean, peas, and cabbage. None of these crops have cultivars that are resistant to nonselective herbicides (e.g., glyphosate), which is commonly used in Midwest field corn and soybean production. Weed escapes and seed production are likely greater in vegetable crops, compared to agronomic crops, which might explain the higher atrazine use rates in sweet corn following vegetable crops.

Atrazine was a small portion of growers' expenditures on weed management in sweet corn. Of the 114 fields receiving atrazine, on average growers spent an estimated $7.50/ha on atrazine, accounting for 9% of the total weed management costs.

Implications. Some recent developments in weed management have occurred since the time of this survey. Topramezone was registered for use in sweet corn in 2006 and tembotrione was registered in 2008. Both are new HPPD-inhibiting herbicides and their use likely has increased. In addition, sethoxydim recently was registered for use on a limited number of sethoxydim-resistant sweet corn hybrids that are commercially available. Recent elucidation of the genetic basis for sweet corn hybrid sensitivity to certain P450-metabolized herbicides, and the chromosomal location of those genes are enabling plant breeders to improve crop tolerance (Nordby et al. 2008). Although these developments might offset use of certain POST herbicides reported in Table 2, their impact on future atrazine use is expected to be negligible.

This research provides a contemporary assessment of weed management systems being deployed in sweet corn. Selective herbicides are relied upon heavily, and atrazine is the most frequently used herbicide; it provides the majority of the broadleaf weed control. Atrazine, applied PRE, accounts for the majority of the amount applied; however, atrazine POST applications are common. This study shows that loss of atrazine would directly affect two-thirds of the sweet corn production area. If atrazine were phased out completely, we hypothesize the greatest burden would be to those growers who (1) rely on less tillage for weed control, (2) have particularly weedy fields, (3) have early season crop production, and (4) grow sweet corn in rotation with other vegetables. Based on the extent of atrazine use and average PRE and POST use rates of atrazine and mesotrione from this work, it is estimated that the annual net cost to replace atrazine in sweet corn with the broad spectrum broadleaf herbicide, mesotrione, is $9.2 million. Swanton et al. (2007) found no alternative herbicide with equal economic and agronomic benefits in field corn, and the same appears true of sweet corn. Furthermore, atrazine might play an even larger role in sweet corn. Relative to field corn, fewer herbicides are registered, especially glyphosate, which is used extensively on glyphosate-resistant hybrids. Also, lower plant populations, reduced seedling vigor, and poorly competitive plant types are characteristic of sweet corn production (Anonymous 2003; So et al. 2009; Tracy 2001). Regardless of atrazine's future, additional research is necessary to develop weed management systems to meet the demands for sustainability. This assessment can help frame the questions and hypotheses for future research on weed management in sweet corn.

Sources of Materials

[1] SYSTAT Software, Version 11.0, Systat Software Inc., 501 Canal Blvd. Suite E, Point Richmond, CA 94804.

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