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Performance consistency of reduced atrazine use in sweet corn

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ABSTRACT

Atrazine is the most widely used herbicide in North American corn production; however, additional restrictions on its use in the near future are conceivable. Currently, a majority of commercial sweet corn fields suffer losses due to weeds, despite widespread use of atrazine. Field experiments were conducted in the primary North American production areas of sweet corn grown for processing to determine the implications of further reductions in atrazine use on weed control and crop yield. A range of atrazine doses (0–1120 g ha^{-1}) applied postemergence with tembotrione (31 g ha^{-1}) were tested in two hybrids differing in canopy architecture and competitive ability with weeds. Atrazine applied postemergence reduced risk (i.e. more variable outcomes) of poor herbicide performance. Atrazine doses up to 1120 g ha^{-1} with tembotrione improved grass control and broadleaf weed control in five of eight and seven of eight environments, respectively. Of the three environments which had particularly low broadleaf weed control (<50%) with tembotrione alone, sweet corn yield was improved with atrazine. Hybrid 'Code128' produced a taller, denser canopy which was more efficient at capturing light and competing with weeds than 'Quickie'. As a result, greater crop competitiveness decreased risk of incomplete weed control as atrazine dose was reduced. Atrazine's contribution to weed control and yield protection was greatest when other aspects of weed management resulted in poor weed control. Should atrazine use be further restricted or banned altogether, this research demonstrates the importance of improving other aspects of weed management systems such as herbicidal and non-chemical tactics.

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1. Introduction

Atrazine is the single most widely used herbicide in North American corn production. Registered for use 50+ years ago (LeBaron et al., 2008), atrazine is applied preemergence (PRE) and postemergence (POST) to control a wide variety of broadleaf and grass weeds. Atrazine has been the subject of considerable debate over potential human health and environmental concerns, prompting the U.S. Environmental Protection Agency (EPA) to recently launch a comprehensive reevaluation of atrazine (EPA, 2009). Based on the outcomes of the current reevaluation, EPA may revise its current atrazine risk assessment and determine if new restrictions are necessary. To date, an economically comparable herbicide alternative to atrazine does not exist (Swanton et al., 2007). The extent to which atrazine use can be reduced while maintaining performance consistency (i.e. weed control and yield protection) in current weed management systems is lacking.

Atrazine is particularly important in sweet corn production. Atrazine is used in most fields at an average rate of 1.35 kg ha^{-1}, yet represents only 9% of total weed management costs (Williams et al., 2010). The herbicide is tank-mixed with other PRE and POST herbicides to improve their performance. Even the newest family of herbicides, those inhibiting 4-hydroxyphenylpyruvate dioxygenase (HPPD), are recommended to be tank-mixed with atrazine to improve weed control (Abendroth et al., 2006). Despite widespread use of atrazine and several other herbicides, over one-half of sweet corn fields suffer yield losses due to weed interference (Williams et al., 2008c). The extent to which further restrictions, or a complete ban, of atrazine has unknown consequences for corn production. This is especially true of sweet corn, which has fewer registered herbicides than field corn and presently lacks hybrids resistant to nonselective herbicides (e.g. glyphosate). Further restrictions or a complete ban of atrazine conceivably would increase risk (i.e. more variable outcomes) to weed control and crop yield.

Sweet corn is grown for the fresh market or processed as a canned or frozen vegetable. Over 60% of U.S. sweet corn acreage is grown for processing (Anon., 2006). Two major production areas account for nearly all of the processed sweet corn in North America, including the North Central Region (NCR) and Pacific Northwest

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(PNW). The NCR has a humid continental climate and production is mostly rainfed. In contrast, production in the PNW is primarily located in a semi-arid climate and is mostly irrigated.

Improving weed management systems in sweet corn is complicated by large variability among hybrids in plant architecture and competitiveness with weeds. Vertical leaf orientation can vary among hybrids, where leaves are entirely upright, to leaves positioned below the leaf collar (So et al., 2009a). Wild-proso millet (*Panicum miliaceum* L.) fitness was negatively correlated with leaf area index (LAI) after crop silking (Williams et al., 2007). So et al. (2009b) evaluated 18 phenomorphological traits of 23 sweet corn hybrids and identified three principal factors linked to crop competitive ability with wild-proso millet. Unlike field corn (Ford and Pleasant, 1994; Roggenkamp et al., 2000), differences in morphology and competitive ability among commercial sweet corn hybrids have significant implications to weed management, whereby some hybrids suffer greater yield losses due to grass interference (Williams et al., 2008b). When atrazine use is reduced, hybrids with poorer competitive ability may disproportionally release grass and broadleaf weeds and suffer higher crop losses.

Experiments were conducted in the primary North American production areas of sweet corn grown for processing to determine the implications of further reductions in atrazine use on weed control and crop yield. Because commercial hybrids differ in competitive ability, we also tested the hypothesis that maintaining weed control at reduced atrazine doses would depend in part on the level of competition exerted by the hybrid.

2. Materials and methods

Field experiments were conducted two years each in Urbana, Illinois, USA (40°6′35″N, 88°12′15″W, 222 m a.s.l.), Corvallis, Oregon, USA (44°34′14.81″N, 123°16′33.59″W, 68 m a.s.l.), Prosser, Washington, USA (46°12′25″N, 119°45′56″W, 203 m a.s.l.), and Ridgetown, Ontario, Canada (42°26′26″N, 81°53′3″W, 198 m a.s.l.) from 2007 to 2009, totaling eight environments. Illinois and Ontario are in the NCR, while Oregon and Washington are in the PNW. Sweet corn was grown using standard practices to achieve yields common to each locale (Anon., 2003, 2006; OMAFRA, 2006).

2.1. Experimental approach

The experimental design was a split plot arrangement within a randomized complete block with four to six replications at each location. Main plots consisted of two homozygous *sugary1* sweet corn hybrids, 'Quickie' and 'Code128'. These two hybrids were selected because they are grown in North America and represent the range of competitive abilities with wild-proso millet among commercial hybrids (So et al., 2009a). Three-meter wide main plots (four 0.76-m spaced rows) were divided into 9.1 m long subplots, which were assigned one of the five atrazine doses (0, 41, 123, 370, and 1120 g ha^{-1}) applied postemergence (POST) with 31 g ha^{-1} of tembotrione, the 1/3X label dose of the HPPD-inhibitor most recently registered in U.S. sweet corn. The tembotrione dose chosen for this study is consistent with how sweet corn growers are using HPPD-inhibiting herbicides below registered use rates (Williams et al., 2010). A season-long weed-free plot was included, and maintained by a preemergence application of 1.7 kg ha^{-1} of atrazine plus 1.8 kg ha^{-1} of metolachlor or dimethenamid at 1.1 kg ha^{-1} and weekly handweeding as needed. Postemergence herbicides were applied to corn with four or five visible collars, approximately one month after planting (Table 1). Application included 1% crop oil concentrate and 2.5% urea ammonium nitrate (28% nitrogen) in 187 l ha^{-1} of spray volume.

Table 1
Planting dates, dates of postemergence (POST) herbicide treatment, and weed population densities at the time of POST treatment.

Location	Year	Planting date	POST date	Grasses[a] no. m^{-2}[b]	ABUTH	AMASP	CHEAL	POROL	SOLSP	SASKR
Illinois	2007	5 May	1 June	1.1 (1–2)	1.8 (C–1)	23.3 (C–1)	1.6 (C–1)	3.8 (C)	0.1 (C)	–
	2008	6 May	5 June	215.5 (2–5)	2.5 (3–9)	33.9 (12–15)	124.8 (9–20)	18.9 (5–15)	5.3 (6–9)	–
Oregon	2007	23 May	23 June	1.2 (3–6)	–	8.6 (4–8)	0.4 (4–8)	42.8 (4–6)	27.8 (4–8)	–
	2008	14 May	18 June	Present[c]	–	2.6 (C–8)	5.3 (C–8)	134.9 (C–6)	147 (C–8)	–
Washington	2007	18 May	14 June	6.3 (1–T)	–	0.5 (C–12)	0.3 (5–7)	–	16.4 (C–9)	0.5 (5–7)
	2008	19 May	16 June	137.7 (3–4)	–	8.9 (5–6)	1.6 (6–8)	2.2 (6–10)	130.5 (7–9)	0.1 (5–7)
Ontario	2008	28 May	21 June	21.3 (2–3)	147.3 (C–4)	37.8 (C–4)	19.3 (C–4)	–	–	–
	2009	20 May	14 June	0.3 (3–5)	12.3 (C–4)	0.8 (2–6)	5.3 (C–8)	–	0.3 (2–3)	–

[a] *Abbreviations*: grassy weeds including barnyardgrass, fall panicum, large crabgrass, wild-proso millet, and witchgrass; ABUTH, velvetleaf; AMASP, weeds of the Amaranthus genus including common waterhemp, Powell amaranth, and redroot pigweed; CHEAL, common lambsquarters; SOLSP, weeds of the Solanum genus including black nightshade, eastern black nightshade, and hairy nightshade; SASKR, Russian thistle.

[b] Parenthetical values are range of growth stages, where number is leaf number, 'C' is cotelydon, and 'T' is tillering.

[c] Witchgrass observed, but density and growth stages not identified.

Immediately prior to POST application, range of growth stages and density of weed species were recorded in a total area of 1-m^2 per plot. Weed control was evaluated two weeks after treatment (2WAT) and at the time of sweet corn harvest. 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. The date when at least 50% of sweet corn plants in weed-free plots had silks emerged from the ear shoot (i.e. anthesis) was recorded. Within a week of silking, crop canopy density in weed-free plots was measured for height, LAI, and intercepted photosynthetically active radiation (IPAR) as described by Williams et al. (2006). Marketable ears, measuring ≥ 4.5 cm in diameter with husks, were hand-harvested at maturity of each hybrid from the two center rows over 6.0 m of row, and ear mass and number were recorded. For each environment, relative yield was calculated as yield at a given atrazine dose divided by average weed-free yield. Relative yield was calculated for both marketable ear mass and number. Crop population density within the harvest area also was recorded. Daily minimum and maximum temperature and rainfall data were obtained from a weather station nearby each site with water supply from irrigation added to the data. Growing degree days (GDD) accumulated from crop emergence were calculated with a base temperature of 10 °C.

2.2. Data analysis

Crop canopy, weed-free yield, relative yield, and weed control data were analyzed for homogeneity of variances using the modified Levene's test (Neter et al., 1996). Variances were found to be nonhomogeneous among environments; therefore, analyses were performed within each environment. Diagnostic tests of residuals indicated weed control met assumptions of homogeneity of variance and normality after arcsine transformation, while other response variables met these assumptions without transformation. Analysis of variance for each response variable was conducted using general linear models in SYSTAT version 11.0.1 (SYSTAT, 2004).

Potential links among atrazine dose, weed control, crop canopy variables, and yield were investigated using path analysis. Path analysis is a multiple regression method that specifies potential causal pathways between two or more independent and dependent variables of interest, accounting for correlations between variables and unexplained (latent) sources of error (Mitchell, 2001). The RAMONA subroutine of SYSTAT was used to estimate standardized regression coefficients and latent variables of yield for a single path analysis model for each atrazine dose, across hybrids and environments. Variables included weed control 2WAT and at harvest, crop LAI, and observed yield as measured by ear mass.

3. Results

3.1. Environmental conditions

Temperature and crop development during the growing season were typical of each location. Days from planting to emergence ranged from six to eight days in the PNW, and seven to 11 days in the NCR. Length of the growing season, from emergence to harvest, averaged 68 days in Illinois and Ontario. In contrast, this period took on average 78 and 93 days at Washington and Oregon, respectively.

Experiments in Oregon and Washington received routine irrigation to supplement limited rainfall (<15% of total water supply). In contrast, experiments in Ontario were not irrigated, and Illinois received a single irrigation event in 2007 to offset abnormally dry conditions. Total water supply from emergence to average harvest date was 35, 32, 53, and 16 cm for Illinois, Oregon, Washington, and Ontario, respectively.

3.2. Weed communities

Commonality in weed community composition across locations was limited. Common lambsquarters (*Chenopodium album* L.) was the only species observed in every environment (Table 1). Plants of the Amaranthus genus were observed throughout the study; however, Powell amaranth (*Amaranthus powellii* S. Wats.) dominated PNW locations while common waterhemp (*Amaranthus rudis* Sauer) and redroot pigweed (*Amaranthus retroflexus* L.) dominated NCR locations. Likewise, plants of the Solanum genus were often observed; however, hairy nightshade (*Solanum physalifolium* Rusby) dominated PNW locations while eastern black nightshade (*Solanum ptychanthum* Dunal) dominated NCR locations. Velvetleaf (*Abutilon theophrasti* Medik.) was observed only in NCR locations, whereas Russian thistle (*Salsola tragus* L.) was observed only in Washington. Multiple species of grasses were observed at each location, including barnyardgrass (*Echinochloa crus-galli* (L.) Beauv.), fall panicum (*Panicum dichotomiflorum* Michx.), large crabgrass (*Digitaria sanguinalis* (L.) Scop.), wild-proso millet, and witchgrass (*Panicum capillare* L.).

Weed infestations at the time of POST treatments were often high. Total population densities ranged from 19 to 400 plants m^{-2} (Table 1). Each location had a year in which total population densities were lower than 81 plants m^{-2}, and a year in which total population densities were higher than 281 plants m^{-2}. Common lambsquarters ranged from 0.3 to 124.8 plants m^{-2} across environments. Also, plants were often in a range of growth stages. Broadleaf weeds often had six or more leaves and the largest grasses ranged in size from three leaves to tillering. One exception to a high infestation was in Illinois 2007. The crop was planted into moisture and grew well; however, lack of rainfall until immediately before POST application delayed weed emergence. As a result, the crop had a significant size advantage over the late emerging weed community.

3.3. Crop traits

Hybrid 'Code128' was of longer maturity than 'Quickie'. On average, thermal time from emergence to silking for 'Quickie' was 438 GDD, or 46 days. In contrast, 'Code128' on average required 653 GDD, or 65 days, to achieve silking. These differences in maturity led to canopy traits which also differed among hybrids. Hybrid 'Code128' produced a taller, denser canopy which was more efficient at capturing light than 'Quickie'. For instance in every environment, LAI was greater in 'Code128' than 'Quickie', averaging 4.43 and 2.49 m^2 m^{-2}, respectively (Table 2). Similar patterns were observed for plant height and IPAR. Within each environment, crop population density often was similar between hybrids. One exception was Washington 2008, in which 'Quickie' had 17% more plants than 'Code128'.

3.4. Weed control

Atrazine doses up to 1120 g ha^{-1} improved grass control with tembotrione in five of eight environments, as evidenced by significant p-values ($\alpha = 0.05$) for the effect of dose on grass control (Fig. 1). Without atrazine, average grass control at harvest within an environment was often below 90%, and as low as 44% in Washington 2007. In contrast, average grass control at 1120 g ha^{-1} exceeded 95% in most environments.

Grass control was higher in 'Code128' than 'Quickie' in three of eight environments, and at no time was 'Quickie' superior (Fig. 1). Improved grass control in 'Code128' was observed across a range of doses in Illinois 2008, Oregon 2007, and Washington 2008.

Similar results were observed for broadleaf weed control at harvest. Atrazine doses up to 1120 g ha^{-1} improved broadleaf weed control with tembotrione in seven of eight environments (Fig. 2).

Table 2
Height (HT), leaf area index (LAI), intercepted photosynthetically active radiation (IPAR) after silking and yield of sweet corn hybrids ‘Code128’ and ‘Quickie’ in weed-free plots.[a]

Location	Year	Hybrid	HT (cm)	LAI (m^2 m^{-2})	IPAR (%)	Yield (Mt ha^{-1})
Illinois	2007	Code128	214*	5.19*	82.5*	21.1*
		Quickie	85	2.70	61.4	12.1
	2008	Code128	219*	4.91*	93.9*	29.4*
		Quickie	117	2.84	75.5	16.1
Oregon	2007	Code128	247*	3.78*	96.1*	31.4*
		Quickie	138	2.02	81.9	15.3
	2008	Code128	278*	4.36*	–	29.7*
		Quickie	139	3.22	–	14.9
Washington	2007	Code128	204*	3.97*	96.8*	29.9*
		Quickie	122	1.60	68.4	14.3
	2008	Code128	219*	3.27*	88.4*	16.6
		Quickie	158	1.43	71.7	16.3
Ontario	2008	Code128	–	4.90*	80.9*	14.8
		Quickie	118	2.80	56.8	12.4
	2009	Code128	171*	5.05*	82.3*	12.7*
		Quickie	106	3.27	58.7	8.2
	Average	Code128	222	4.43	88.7	24.1
		Quickie	123	2.49	67.8	13.9

[a] Within each state-year, an asterisk denotes hybrids differed at $p < 0.05$.

The one exception was in Illinois 2007, in which the crop had a size advantage over the late emerging weed community, as noted earlier. In all other environments, average broadleaf weed control with tembotrione was improved from 70% without atrazine to 95% with 1120 g ha^{-1} atrazine.

Likewise, broadleaf weed control was higher in ‘Code128’ than ‘Quickie’ in five of eight environments (Fig. 2). In four of these environments, ‘Code128’ was better at maintaining broadleaf weed control than ‘Quickie’ as atrazine dose was reduced, as evidenced by significant interactions between hybrid and dose.

3.5. Crop yield

Mean weed-free yields ranged from 8.2 to 31.4 Mt ha^{-1}, depending on environment and hybrid. Weed-free yields of ‘Code128’ were higher than ‘Quickie’ in six environments (Table 2).

Atrazine doses up to 1120 g ha^{-1} with tembotrione improved ear mass yield in three of eight environments (Fig. 3). These environments, Illinois 2008, Ontario 2008, and Ontario 2009, had particularly poor broadleaf weed control (<50%) without atrazine. Averaged across hybrids in these three environments, relative mass yield improved from 47% with tembotrione alone to 95% with tembotrione plus 1120 g ha^{-1} of atrazine. In all other environments, yields averaged 97% or more of the weed-free yield across atrazine dose. Nearly identical results were observed with yield as measured by marketable ear number (data not shown).

Relative yield varied by hybrid and environment, but only in environments where yield was high regardless of atrazine dose, as mentioned above. For instance, ‘Code128’ maintained yield better than ‘Quickie’ in one environment, Illinois 2007, whereas the opposite was true in Ontario 2008 and Washington 2008 (Fig. 3).

3.6. Path analysis

The path analysis model related the associations of weed control at multiple observation times and crop canopy density after silking both directly and indirectly to crop yield (Fig. 4). When atrazine was applied at 1120 g ha^{-1} with tembotrione, a positive path coefficient (0.759, $p \leq 0.01$) was observed for the relation between weed control 2WAT and weed control at harvest. At this dose, crop LAI after silking had a direct effect on yield (0.479, $p \leq 0.01$), but not on weed control observed at harvest. The indirect effect of weed control 2WAT, mediated through weed control at harvest, was positive (0.300) though at a larger p-value ($p \leq 0.05$) than the direct effect of crop LAI.

The path analysis model showed distinct changes in the relationships among weed control, canopy density, and crop yield as atrazine dose was reduced (Fig. 4). The path coefficient linking weed control 2WAT to weed control at harvest remained significant ($p \leq 0.01$) but declined numerically from 0.759 to 0.361 as atrazine dose was reduced from 1120 to 0 g ha^{-1}, indicating the effect of higher atrazine doses on weed control carried through to harvest to a greater extent than at lower doses. At doses below 1120 g ha^{-1}, level of weed control at harvest improved as a predictor of crop yield, as evidence by larger, more significant path coefficients. This result was observed because at-harvest weed control often varied more at doses below 1120 g ha^{-1} (Figs. 1 and 2), resulting in a greater range of competitive effects from the weed community. Moreover, when atrazine use was reduced below 123 g ha^{-1}, the contribution of crop competitive ability to weed suppression was revealed, as evidenced by positive path coefficients (≥0.232) linking crop LAI to at-harvest weed control. This trend occurred concomitantly with a weakening of the direct relationship between crop LAI and yield.

4. Discussion

This study quantified the significance of atrazine use across a diversity of conditions in which sweet corn is grown for processing in North America. The two major areas of processing sweet corn production, NCR and PNW, were both represented with two years at each of two locations. Average water supply (16–53 cm) and days (68–93) from emergence to harvest capture, in part, variability in key environmental conditions among study locations. In addition, observed weed communities in experiments showed the significance of weed infestations (up to 400 plants m^{-2}), with dominant species varying among locations and years. Finally, the two hybrids used in the experiments, both of which are commercially available and grown, had a range of values for traits that are important to competitive ability with weeds (e.g. IPAR average of 68 and 89%).

Atrazine applied POST reduces risk of herbicide failure and sweet corn losses. Atrazine improved grass and broadleaf weed control with tembotrione in most fields. One exception was a case where the crop had a significant size advantage over the late-

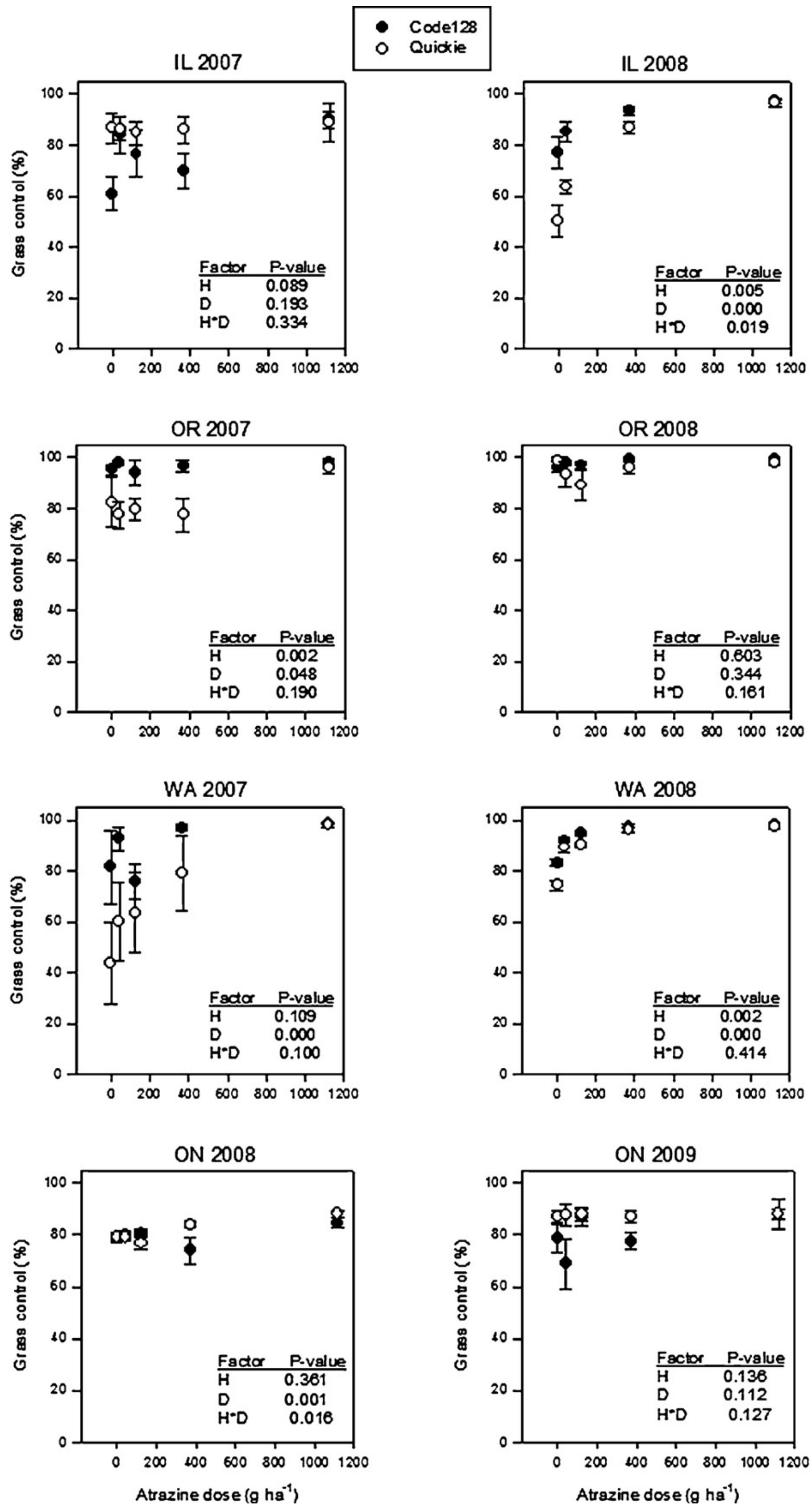

Fig. 1. Mean grass control (with standard error bars) at the time of harvest in sweet corn hybrids 'Code128' and 'Quickie' as a function of postemergence atrazine dose for field experiments conducted in Urbana, Illinois (IL), Corvallis, Oregon (OR), Prosser, Washington (WA), and Ridgetown, Ontario (ON), 2007–2009. Analysis of variance *p*-values for each environment are reported for the main effects of hybrid (H) and atrazine dose (D), and the interaction term (H*D).

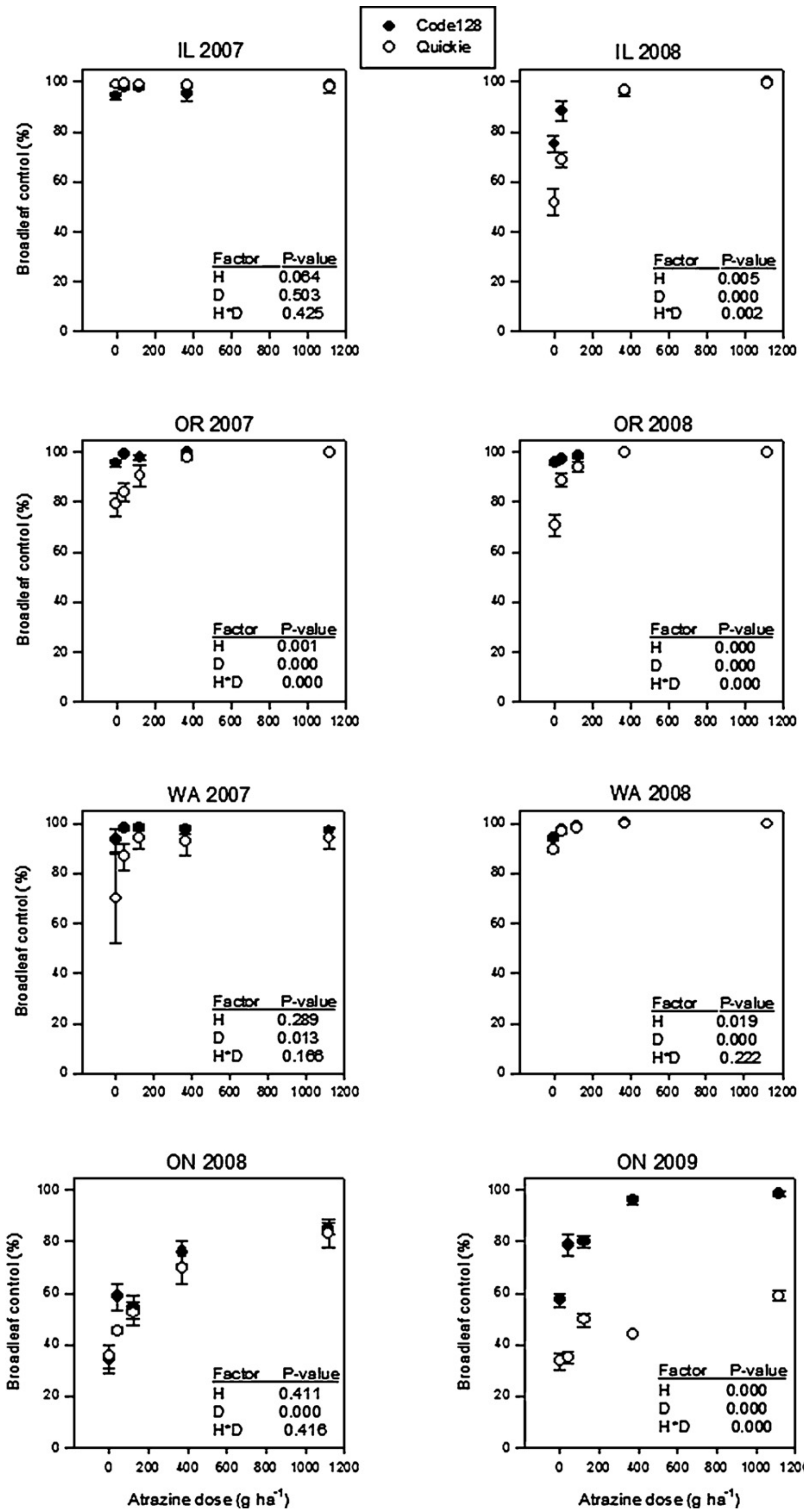

Fig. 2. Mean broadleaf weed control (with standard error bars) at the time of harvest in sweet corn hybrids 'Code128' and 'Quickie' as a function of postemergence atrazine dose for field experiments conducted in Urbana, Illinois (IL), Corvallis, Oregon (OR), Prosser, Washington (WA), and Ridgetown, Ontario (ON), 2007–2009. Analysis of variance *p*-values for each environment are reported for the main effects of hybrid (H) and atrazine dose (D), and the interaction term (H*D).

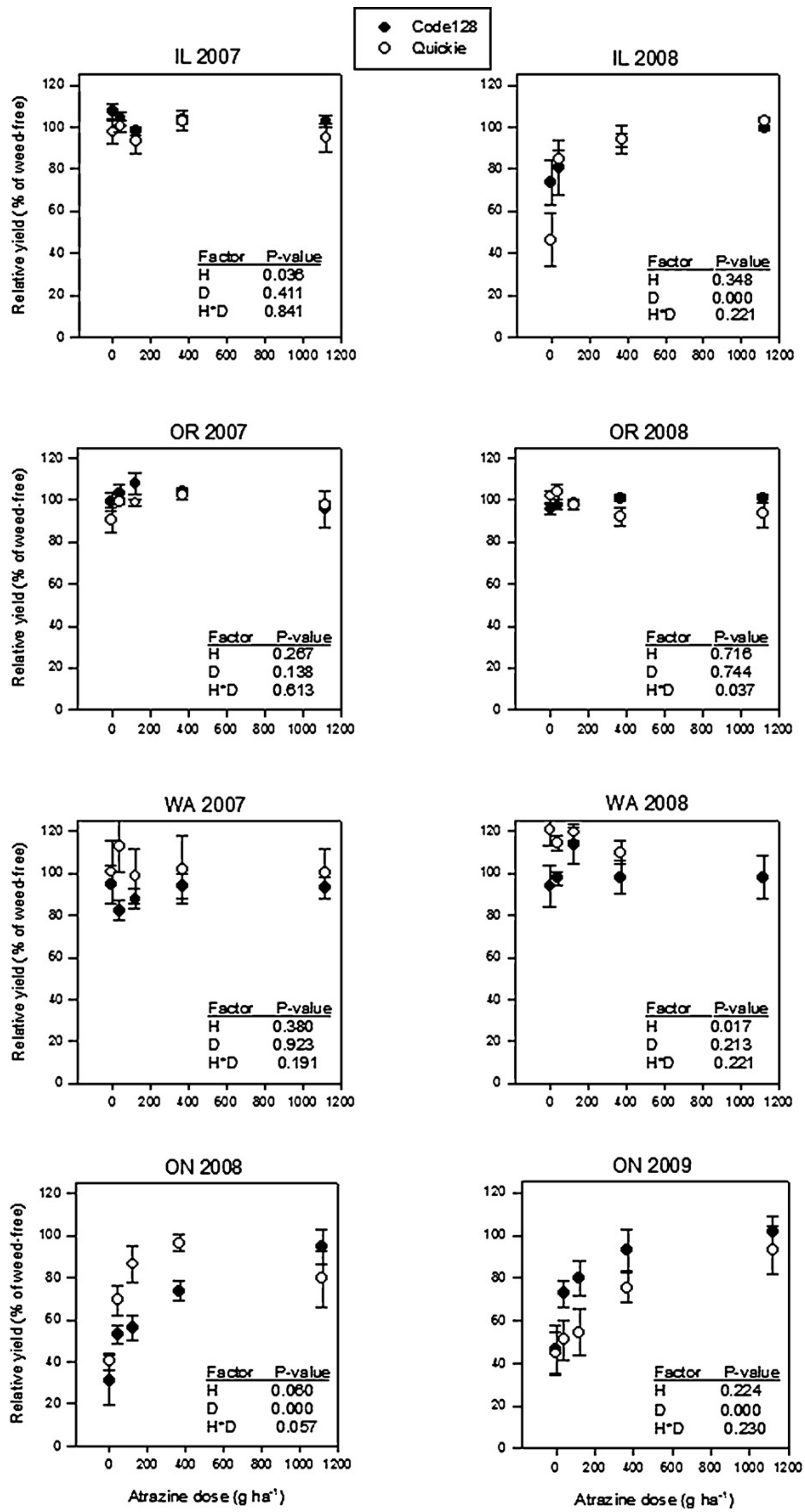

Fig. 3. Relative yield (% of weed-free, with standard error bars) of sweet corn hybrids 'Code128' and 'Quickie' as a function of postemergence atrazine dose for field experiments conducted in Urbana, Illinois (IL), Corvallis, Oregon (OR), Prosser, Washington (WA), and Ridgetown, Ontario (ON), 2007–2009. Analysis of variance *p*-values for each environment are reported for the main effects of hybrid (H) and atrazine dose (D), and the interaction term (H*D).

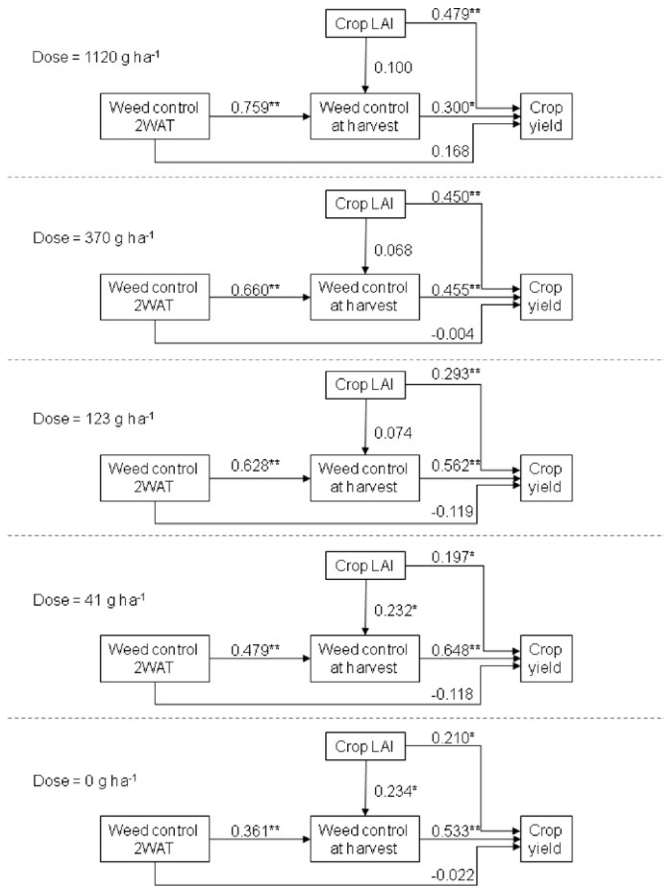

Fig. 4. Path analysis model for comparing weed control two weeks after herbicide treatment (2WAT), weed control at crop harvest, crop leaf area index after silking (LAI), and sweet corn yield at five doses of atrazine applied postemergence. Standardized regression coefficients denoted with asterisks, * and **, are significant at $p \leq 0.05$ and $p \leq 0.01$ levels, respectively.

emerging weed community. Of fields that were most weedy (<50% control with tembotrione alone), atrazine also improved crop yield. Swanton et al. (2007) also saw poorer efficacy of several POST herbicides in some fields when atrazine was not included, and that improved weed control with addition of atrazine did not always translate into yield gains in field corn. The beginning of the critical period of weed control (CPWC) in May-planted sweet corn (at 5% yield loss) is at four-collar sweet corn (Williams, 2006). In the present work, POST applications were made near this CPWC threshold. In some cases, tembotrione alone did not provide complete weed control, but provided adequate suppression during the CPWC to avert yield loss. Atrazine's improvement to weed control occurred widely; however, its contribution to yield protection was only detected when tembotrione alone resulted in particularly poor weed control.

Poorer crop competitiveness increased occurrence of incomplete weed control. Compared to 'Code128', 'Quickie' was deficient in several canopy traits conferring competitiveness against wild-proso millet (So et al., 2009a), including plant height, LAI, and IPAR. In competition with a more diverse weed community in this work, grass and broadleaf weed control often was poorer in 'Quickie' than 'Code128', particularly as atrazine dose was reduced below 1120 g ha^{-1}. This work is consistent with Lemerle et al. (1996) and Kim et al. (2002), who have found poorly competitive wheat cultivars require greater dependence on herbicides for providing weed suppression. In previous work (Williams et al., 2008a), we reported graminicide performance was often influenced by sweet corn hybrid. Interestingly, the improved weed control in 'Code128' treatments did not transpire into consistent improvements in yield protection at those locations. So et al. (2009b) showed tight linkages between the crop traits that confer weed suppressive ability (WSA) and crop tolerance (CT) to weed interference. In work using wild-proso millet, sweet corn hybrids that had greater WSA often had greater CT (Williams et al., 2007, 2008a, 2008b). In the present work, relative yield was high regardless of atrazine dose in some cases (e.g. Oregon); hence, intensity of weed interference was insufficient to cause yield loss, let alone a differential response among hybrids. In other cases, a large range of weed control resulted in a large range of crop yield (e.g. Ontario); nonetheless, consistent differences in hybrid yield responses were not observed.

Several crop traits are involved in competitive ability with weeds. Crop LAI reflects only one of the several co-dependent predictor variables of competitive ability. Conceivably, crop competitive ability contributed to weed control at atrazine doses beyond 0 and 41 g ha^{-1} as observed in the path analysis. Perhaps the path model using other canopy traits not measured in this work, or principal canopy factors linked to competitive ability (So et al., 2009b), would reveal contribution of competitive ability across a wider range of atrazine doses. Nonetheless, results confirm our hypothesis that crop competitive ability influenced weed control, most notably as atrazine dose was reduced to zero.

The contribution of atrazine to weed control and yield protection was greatest when other aspects of weed management resulted in poor weed control. Sweet corn production did not benefit from atrazine applied POST in every environment, but most. The weed management system studied in this work is characteristic of current grower practices (Williams et al., 2010), including conventional tilled seedbed, no interrow cultivation, and a single application of POST herbicides. We applied tembotrione at 1/3X the label dose; consistent with a majority of growers who apply HPPD-inhibiting herbicides below label doses (Williams et al., 2010), perhaps to lower costs with these more expensive herbicides (~\$37 ha^{-1}; Boerboom et al., 2008). Because atrazine is inexpensive (~\$5 ha^{-1}; Boerboom et al., 2008), its use enables growers to reduce risk of variable weed control and potential crop losses at minimal cost.

5. Conclusion

Without improving other aspects of current weed management systems, additional reductions in atrazine use in sweet corn production will result in poorer weed control and even greater crop losses. Although chemical weed control is common throughout North American corn production, a simple replacement herbicide for atrazine is unlikely. Currently, no alternative herbicide provides comparable economic and agronomic attributes as atrazine (Swanton et al., 2007). Although beyond the scope of this paper, more herbicides and higher doses may offset loss of atrazine at higher expense. Additional opportunities to improve weed management may reside in the integration of non-chemical tactics. For instance, crop rotation and mechanical weed control are underutilized in sweet corn production. In the NCR, 74% of fields are grown in a corn-corn monoculture or corn-soybean rotation (Williams et al., 2010). Interrow cultivation is used on only one-half of fields. Greater atrazine use was observed in fields lacking interrow cultivation, compared to fields where interrow cultivation was deployed (Williams et al., 2010). Perhaps planting date could be considered for particularly weedy fields. In previous work we found in a temperate climate that sweet corn is more competitive with common NCR weeds in June and July plantings (Williams, 2006, 2009). Indeed, later planting dates and harvest dates of commercial fields were associated with reduced weed diversity and interference (Williams et al., 2008c, 2009). The present work shows utilizing a more competitive crop lowered the risk of more variable weed control associated with atrazine use reduction; however, even one of the most competitive commercial hybrids was not immune to losses due to weed interference. A complexity of multiple and variable weed control tactics is believed to be more robust over time than weed management systems dominated by a single tactic (Liebman and Gallandt, 1997; Westerman et al., 2005). Loss of atrazine use may necessitate migration towards more complex weed management systems.

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