Crop competitive ability contributes to herbicide performance in sweet corn

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Summary

Crop variety effects on herbicide performance is not well characterised, particularly for sweet corn, a crop that varies greatly among hybrids in competitive ability with weeds. Field studies were used to determine the effects of crop competitive ability on season-long herbicide performance in sweet corn. Two sethoxydim-tolerant sweet corn hybrids were grown in the presence of *Panicum miliaceum* and plots were treated post-emergence with a range of sethoxydim doses. Significant differences in height, leaf area index and intercepted light were observed between hybrids near anthesis. Across a range of sub-lethal herbicide doses, the denser canopy hybrid Rocker suppressed *P. miliaceum* shoot biomass and fecundity to a greater extent than the hybrid Cahill. Yield of sweet corn improved to the level of the weed-free control with increasing sethoxydim dose. The indirect effect of herbicide dose on crop yield, mediated through *P. miliaceum* biomass reduction, was significant for all of the Cahill's yield traits but not Rocker. These results indicate that a less competitive hybrid requires relatively more weed suppression by the herbicide to not only reduce weed growth and seed production, but also to maintain yield. Sweet corn competitive ability consistently influences season-long herbicide performance.

Keywords: competition, cultivar, dose–response, herbicide, integrated weed management, risk, sethoxydim, *Zea mays*.

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Introduction

Weed management in North American sweet corn (*Zea mays* L.) production is characterised by reliance on soil applications of triazine and chloroacetamide herbicides (Anonymous, 2003) and risk of crop injury from several post-emergence herbicides (Pataky *et al.*, 2006). Recent surveys of commercial production fields in the United States reported extensive weed abundance and fecundity at harvest and 58% of the fields suffered yield loss because of weed interference (Williams *et al.*, 2006c). Weed interference differentially affects yield and ear traits important to both processing and fresh markets (Williams & Masiunas, 2006). In light of these challenges, weeds present in sweet corn production and particularly in a growing organic market mean that improved weed management systems are a top priority to the industry (Anonymous, 2003).

Commercially grown sweet corn germplasm varies widely in competitive ability, defined here as the collective measure of both crop tolerance to weed interference and the crop's ability to suppress weeds. Large differences among hybrids' ability to suppress *Panicum miliaceum* L. (wild proso millet) have been shown to be negatively correlated with leaf area index (LAI) and intercepted photosynthetically active radiation (PAR) after crop anthesis (Williams *et al.*, 2007). Factors driving yield loss varied among sweet corn hybrids; more competitive hybrids established canopy dominance, restrained weed growth and experienced less yield loss (Williams *et al.*, 2008). While crop competitive ability is likely to have practical implications in sweet

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corn, the cumulative effect of competitive ability with other weed management tactics is poorly understood. A plausible outcome of weeds surviving post-emergence control tactics is that weed fitness and crop yield loss would be highest in the least competitive cultivars.

Panicum miliaceum is one of the most abundant weeds in North American sweet corn. A weedy race of domesticated proso millet, *P. miliaceum* has natural tolerance to most herbicides used in sweet corn (Shenk *et al.*, 1990) and grain maize (Westra *et al.*, 1990), pre-empts resources from the crop and is a prolific seed producer prior to harvest. Furthermore, *P. miliaceum* seed is readily dispersed by harvest operations and is difficult to remove from sweet corn ears through processing. Until recently, nicosulfuron is one of the few herbicides available to control *P. miliaceum* in North America, but timing is critical (Williams & Harvey, 2000) and crop injury is prevalent in sweet corn germplasm because of mutation of cytochrome P450 gene *Nsf1* in sensitive hybrids (Williams *et al.*, 2006a). Post-emergence-directed applications of sethoxydim have been proposed for *P. miliaceum* suppression in sweet corn (Kleppe & Harvey, 1991). Sethoxydim-tolerant grain maize (Dotray *et al.*, 1993) permits broadcast applications and in 2006 a few sethoxydim-tolerant sweet corn hybrids became available for use in the United States. However, sethoxydim sometimes does not control *P. miliaceum,* because of lack of residual control, especially with early post-emergence applications (Harvey & Porter, 1990).

The degree to which crop variety influences herbicide performance is poorly known. In cropping systems other than maize, several authors have quantified the contribution of crop competitive ability by examining herbicide performance at reduced doses in different cultivars (Christensen, 1994; Lemerle *et al.*, 1996; Kim *et al.*, 2002). Poorly competitive wheat (*Triticum aestivum* L.) cultivars had a greater dependence on herbicides for providing weed suppression and achieving yield potential at sub-lethal herbicide doses (Lemerle *et al.*, 1996; Kim *et al.*, 2002). In the case of *P. miliaceum*, fecundity was suppressed differentially by crops (O'toole & Cavers, 1983) and rapid canopy development of soyabean [*Glycine max* (L.) Merr.] suppressed late germinating *P. miliaceum* after sethoxydim application (Harvey & Porter, 1990). In order for crop competitive ability to make greater contributions to weed management systems, Jordan (1993) argues the value of knowing the degree to which competitive ability can offset reductions in other forms of weed management.

The objectives of this study were to determine the effects of various doses of sethoxydim on season-long suppression of *P. miliaceum* in sweet corn and identify relationships among herbicide dose, crop canopy density, weed suppression and crop yield. The objectives were tested in two sethoxydim-tolerant sweet corn hybrids suspected to differ in competitive ability.

Materials and methods

Site description

Field experiments were conducted in 2005 and 2006 near Urbana, Illinois (40°4'N, 88°12'W) and Prosser, Washington (46°15'N, 119°44'W). The soil at Illinois was a Flanagan silt loam (fine, smectitic, mesic Aquic Argiudoll) averaging at 3.6% of organic matter and a pH of 6.4 and soil at Washington was Warden sandy loam (coarse-silty, mixed, superactive, mesic Xeric Haplocambid) with 0.9% organic matter and pH of 7.0. Experiments were located in different fields in each year. The previous crop was soyabean at Illinois and grain maize at Washington. Fields in Illinois received 129 kg N ha^{-1}, 113 kg P ha^{-1} and 135 kg K ha^{-1} on 16 March 2005 and 12 April 2006. Fields in Washington received 224 kg N ha^{-1}, 59 kg P ha^{-1} and 185 kg K ha^{-1} on 2 May 2005 and 246 kg N ha^{-1}, 56 kg P ha^{-1} and 90 kg K ha^{-1} on 1 May 2006. The experimental area was chisel-ploughed in the fall or spring, followed by one pass each of a disk harrow and a field cultivator prior to planting.

Experimental approach

The experimental design was a split plot with four replications. Sweet corn hybrid was the main plot factor, including Cahill and Rocker. Hybrids were *sugary1* endosperm mutants; however, Cahill matures *c.* 9 days earlier than Rocker. Four-row plots were planted on a row of 76 cm spacing at 70 400 seeds ha^{-1} in Illinois and 77 800 seeds ha^{-1} in Washington using a seeding depth of 3.5 cm. Five doses of sethoxydim [0, 12.5, 25, 50 and 100 g a.i. (active ingredient) ha^{-1}] were assigned to subplots measuring 12.2 m in length and 3.0 m in width. A crop monoculture and weedy monoculture treatment were included. Within 3 days of sweet corn planting, *P. miliaceum* was seeded at a depth of 1.3 cm within the row, to simulate weeds escaping inter-row cultivation. The two central sweet corn rows of each subplot were sown at 75 viable seeds per metre of the row using a cone planter. Crop planting dates were 9th May in Illinois and 8th May in Washington. Seed of *P. miliaceum* was used from biotypes found in each region that had been harvested the previous summer and stored at room temperature.

A pre-emergence application of atrazine at 2.2 kg a.i. ha^{-1} (Illinois) or 1.12 kg a.i. ha^{-1} (Washington) was applied to the study within 3 days of planting. Sethoxydim treatments were applied when a majority of *P. miliaceum* seedlings had three to four leaves. Sethoxydim was applied with a hand-held sprayer calibrated to deliver 130 l ha^{-1} at 276 kPa. All other weeds were removed by hand-weeding and, as needed, a single application of atrazine or carfentrazone.

Experimental sites in Washington were furrow-irrigated on average 47 cm each year. Three (2005) and four (2006) times in Illinois, experimental sites were sprinkler irrigated with 2.5 cm of water to offset abnormally low rainfall.

Data collection

Within 3 weeks of emergence, sweet corn populations were counted by subplot and *P. miliaceum* population density was determined by counting seedlings in three 1 m sections of row per subplot. Percent control of *P. miliaceum* was rated visually 14 and 28 days after sethoxydim treatment (DAT), one exception being that the 28 DAT rating was not quantified one site–year.

Weed-free sweet corn height, LAI and intercepted PAR were quantified during anthesis, the most relevant phenological time related to sweet corn yield (Williams *et al.*, 2006b) and *P. miliaceum* suppression (Williams *et al.*, 2007). Height was determined by measuring 10 plants per subplot from the soil surface to the plant apex. Two plants per subplot were harvested, leaves were separated and green leaf area was measured using an area meter (LI-COR; Lincoln, NE, USA). LAI at each sampling date was estimated as the product of mean leaf area per plant and number of plants per m^2. Quantity of PAR intercepted by the plant canopy was measured near solar noon under full-sun conditions at three locations within each plot using a linear ceptometer (Decagon Devices, Pullman, Washington, DC, USA).

Using the same sampling pattern as for seedling counts, *P. miliaceum* shoots were clipped at the soil surface at the time of sweet corn harvest of each hybrid. Panicles were threshed using a mechanical thresher (Seedburo Equipment Company, Chicago, Illinois, USA) and seeds were cleaned and counted. Shoot biomass was oven-dried at 65°C for 4–6 days and weighed.

Marketable ears were hand-picked 18–21 days after anthesis from the centre two rows over 6.1 m of the row. Illinois harvest dates were 22nd July (Cahill) and 2nd August 2005 (Rocker), and 28th July (Cahill) and 8th August 2006 (Rocker). Washington harvest dates were 12th August (Cahill) and 19th August 2005 (Rocker) and 8th August (Cahill) and 17th August 2006 (Rocker). Ears were considered marketable if kernels were full, yellow and had a moisture content of 75 ± 3%. Ears (including silks + husks) meeting these criteria exceeded 4.4 cm in diameter. Total mass and number of marketable ears (one box = 50 ears) were recorded. At Illinois, fresh ears were also husked with a husking bed (A&K Development, Eugene, OR, USA) and kernels were removed from the cob with an industry-grade corn cutter (A&K Development, Eugene). Husked mass and kernel mass were recorded. Recovery was calculated as the percentage of ear mass represented by kernel mass.

Statistical analyses

Before analyses, all data were examined for homogeneity of variances using the modified Levene's test (Neter *et al.*, 1996). Variances were found to be non-homogeneous between sites and years for all variables except corn seedling population density; therefore analyses were performed within site–year combinations. Diagnostic tests of residuals found intercepted PAR and LAI complied with homoscedasticity and normality after arcsine transformation, while other response variables met ANOVA assumptions without transformation. After ANOVA (SYSTAT Software, Inc., 2004), means were compared using protected Bonferroni-corrected multiple comparisons (Neter *et al.*, 1996) within site–year combinations or among site–years, where appropriate.

A logistic model was used to quantify weed response over a range of sethoxydim doses. *Panicum miliaceum* control, biomass and fecundity were fitted to the logistic model:

$$y = C + \frac{D - C}{1 + \left(\frac{x}{I_{50}}\right)^b} \tag{1}$$

where y is the response variable, x is the sethoxydim dose, C is the lower asymptote, D is the upper asymptote, I_{50} is the dose eliciting 50% reduction in response variable and b is the slope at the I_{50} dose. Constants were used for parameters D and C of Eqn (1) when appropriate (e.g. C fixed at zero when fecundity was eliminated at high doses). Non-linear regression methods were used to fit *P. miliaceum* response to sethoxydim dose for both sweet corn hybrids. Parameter estimates were determined using an iterative least-squares procedure (SYSTAT Software, Inc., 2004). The extra sum of the squares principle for non-linear regression analysis (Ratkowsky, 1983) was employed to evaluate the similarity of parameter estimates between hybrids for each site–year. Comparisons between hybrids were made by calculating a variance ratio of individual and pooled residual sums of squares.

Ritz *et al.* (2006) proposed the use of relative potency to compare dose–response curves between two treatments. The concept of relative potency is equivalent to exchange rates for currencies, so that the relative potency (r) describes the biological exchange rate between the two treatments. When Eqn 1 is used to describe weed response to herbicide dose, the relative potency can be calculated as:

$$r = \frac{I_{50B}}{I_{50A}} \exp[\frac{b_A - b_B}{b_A b_B} \log(\frac{D - C}{\text{dose} - C} - 1)], C < \text{dose} < D \quad (2)$$

where model parameters are those used by fitting *P. miliaceum* biomass and fecundity data to Eqn (1) for hybrid Rocker (A) relative to Cahill (B). When parameters C and D differed between hybrids, relative potency was calculated for the response level range supported by the experiment (Ritz *et al.*, 2006). The two hybrids are equally potent in suppressing *P. miliaceum* when $r = 1$, Cahill is more potent than Rocker when $r < 1$ and Rocker is more potent than Cahill when $r > 1$.

Potential links between sethoxydim dose, crop LAI, *P. miliaceum* biomass and sweet corn yield traits were investigated using path analysis on each hybrid (Jordan, 1989). 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 version 11.0.1 (SYSTAT 2004) was used to estimate standardised regression coefficients and latent variables of yield parameters for a single path analysis model analysed for each sweet corn hybrids within locations but across years. Yield parameters included ear mass and number for both locations and husked mass and kernel mass from Illinois.

Results and discussion

Sweet corn and *P. miliaceum* emerged within a day of each other with one exception. At Washington in 2005, *P. miliaceum* emerged 4 days after the crop (data not shown), largely the result of planting date of the crop preceding the weed by 3 days. No differences in sweet corn seedling density were observed between hybrids, averaging 7.3 and 9.0 seedlings m^{-2} respectively in Illinois and Washington. Measured within 3 weeks of emergence, *P. miliaceum* population densities in Illinois were 43 and 47 seedlings m^{-2} in 2005 and 2006 respectively. In Washington, 78 and 93 *P. miliaceum* seedlings m^{-2} were observed in 2005 and 2006. Natural seedling population densities of *P. miliaceum* prior to management have ranged as high as 360–1200 plants m^{-2} (Wilson & Westra, 1991; Anderson, 2000), although densities observed in this study may be more typical of populations surviving pre-emergence herbicides and tillage.

Table 1 Sweet corn canopy characteristics near anthesis in weed-free plots*

Location	Year	Hybrid	Height (cm)	LAI (m^2 m^{-2})	Intercepted PAR (%)
Illinois	2005	Cahill	179 a	1.6 a	65 a
		Rocker	242 b	3.5 b	91 b
	2006	Cahill	181 a	2.1 a	69 a
		Rocker	248 b	4.6 b	94 b
Washington	2005	Cahill	247 a	3.5 a	96 a
		Rocker	311 b	4.2 a	98 a
	2006	Cahill	261 a	3.1 a	90 a
		Rocker	335 b	5.2 b	97 b

*Within each location–year combination, means followed by the same lower case letter were not significantly different at $P \leq 0.05$ as determined by a protected, Bonferroni-corrected multiple comparison procedure.
LAI, leaf area index; PAR, photosynthetically active radiation.

Canopy density varied between sweet corn hybrids. Rocker produced a taller, more robust plant than Cahill, resulting in Rocker having an advantage for intercepting light. Rocker was 26–28% taller than Cahill in Washington and 35–37% taller in Illinois (Table 1). Rocker averaged 119% more LAI than Cahill in Illinois, although smaller differences (20–67%) were observed in Washington (Table 1). Differences between the hybrids in height and LAI resulted in variable intercepted PAR. Cahill intercepted 65–69% PAR in Illinois, while Rocker intercepted 91–94% PAR (Table 1). Relative to crop canopy development in Illinois, larger growth of both hybrids in Washington resulted in canopies more efficient in intercepting light; however, Rocker intercepted 7% more PAR than Cahill in 1 of the 2 years. The two hybrids in this study created a different light environment for emerged weeds and are comparable with other hybrids grown in North America (Pataky, 1992; Williams *et al.*, 2006b).

Panicum miliaceum *suppression – mid-season*

Although mid-season control of *P. miliaceum* varied by site–year, crop hybrids had no effect on weed response to sethoxydim up to 28 DAT. The dose of sethoxydim resulting in 50% control (I_{50}) ranged from 23.6 to 35.6 g a.i. ha^{-1} at 14 DAT (Table 2). By 28 DAT, the I_{50} dose was 28.3 g a.i. ha^{-1} in all site–years tested (Table 2). These results are in agreement with Harvey and Porter (1990), who tested similar doses of sethoxydim for *P. miliaceum* control.

An effect of crop hybrid on mid-season weed control would be unlikely to be observed, even if late-season canopies differ among hybrids. No differences were observed in sweet corn LAI at the six-leaf stage among

Table 2 Parameter estimates of Eqn 1 for the effect of sethoxydim dose on control of *Panicum miliaceum*. Standard errors of parameter estimates are in parentheses

Time	Location	Year	I_{50} (g a.i. ha^{-1})	B	R^2
14 DAT	Illinois	2005	27.2 (2.1)	−1.8 (0.2)	0.97
		2006	35.6 (7.1)	−1.6 (0.3)	0.92
	Washington	2005	25.3 (0.5)	−2.9 (0.1)	0.99
		2006	23.6 (0.6)	−3.2 (0.2)	0.99
28 DAT	Illinois	2005	28.3 (2.8)	−2.0 (0.3)	0.94
		2006*	–	–	–
	Washington	2005	28.3 (0.6)	−4.1 (0.4)	0.99
		2006	28.3 (0.8)	−3.8 (0.4)	0.98

*Data was not collected at 28 days after treatment.
DAT, days after herbicide treatment; a.i., active ingredient.

three hybrids that, later in the season, varied approximately twofold (Williams *et al.*, 2006b). In this study, the 14 DAT control ratings coincided with the five- to seven-leaf sweet corn. Canopy densities of the two hybrids were similar at 14 DAT (pers. obs.), but obviously differentiated as the season progressed. Any differences in canopy density by the time of the 28 DAT ratings, were apparently either not significant enough or too recent to influence *P. miliaceum* control in this study.

Panicum miliaceum *suppression – season-long*

As the season progressed, *P. miliaceum*'s ability to overcome sub-lethal herbicide dose was influenced by sweet corn hybrid. By the time of harvest, *P. miliaceum* was suppressed to a greater extent by Rocker, compared with Cahill, over a range of sub-lethal doses. In the absence of sethoxydim, *P. miliaceum* biomass was suppressed 42–51% in Illinois and 24–34% in Washington by Rocker, relative to Cahill (*D* parameter of Table 3). *Panicum miliaceum* surviving applications as high as 25 g a.i. ha^{-1} had more biomass in Cahill (Fig. 1). For sethoxydim doses of 50 g a.i. ha^{-1} and more, *P. miliaceum* biomass was similar in both hybrids because control was complete or nearly so. These observations are particularly noteworthy, as, in two of the four site–years, *P. miliaceum* biomass in the weedy monoculture associated with Rocker harvest exceeded weedy monoculture biomass associated with Cahill harvest (Fig. 1). Despite the additional 9–11 days of *P. miliaceum* growth between crop harvest dates, the late-harvested Rocker continued to suppress weed growth below that of Cahill.

While weed growth is important in determining crop losses in the current year, fecundity is the major determinant of the seedbank density and magnitude of future problems. Both sethoxydim dose and sweet corn hybrid influenced the weed's ability to produce seeds. Like biomass, fecundity was nearly eliminated above 50 g a.i. ha^{-1}; however, *P. miliaceum* growing in Cahill produced more seeds at sub-lethal doses (Table 3). In the absence of sethoxydim, *P. miliaceum* fecundity was suppressed 13–71% by Rocker, relative to Cahill. The greater weed-suppressive ability of Rocker is further evidenced by the residual sum of squares test. Within each site–year, the two hybrids had unique dose response functions, with greatest biomass and fecundity across herbicide dose in Cahill (Table 3). Moreover,

Table 3 Parameter estimates of Eqn 1 for the effect of sethoxydim dose on final *Panicum miliaceum* biomass and fecundity. Standard errors of parameter estimates are in parentheses

Response variable	Location	Year	Hybrid	C	D	I_{50}	B	R^2	Sum of squares test*
Biomass	Illinois	2005	Cahill	0.0 (19.8)	210 (18)	24.5 (3.0)	3.4 (1.6)	0.89	a
			Rocker	1.6 (9.2)	122 (10)	15.6 (2.3)	2.9 (1.2)	0.87	b
		2006	Cahill	2.7 (42.9)	167 (26)	47.2 (14.3)	7.0 (34.5)	0.50	a
			Rocker	0.0 (17.3)	81 (12)	39.2 (11.5)	5.4 (5.1)	0.58	b
	Washington	2005	Cahill	0.0 (24.7)	296 (25)	24.9 (1.7)	64.6 (12.3)	0.86	a
			Rocker	2.9 (14.3)	225 (20)	23.1 (15.1)	10.0 (84.2)	0.88	b
		2006	Cahill	20.5 (53.3)	651 (71)	23.4 (14.2)	9.5 (87.5)	0.83	a
			Rocker	9.6 (22.1)	429 (30)	19.6 (2.2)	5.4 (1.9)	0.92	b
Fecundity	Illinois	2005	Cahill	–	5 127 (1000)	18.5 (6.8)	2.1 (1.3)	0.65	a
			Rocker	–	3 008 (403)	12.9 (3.4)	2.0 (1.1)	0.70	b
		2006	Cahill	–	3 566 (543)	43.6 (47.2)	9.5 (73.5)	0.54	a
			Rocker	–	1 034 (203)	40.5 (13.6)	4.2 (4.7)	0.45	b
	Washington	2005	Cahill	–	2 688 (252)	27.2 (5.9)	7.7 (18.9)	0.80	a
			Rocker	–	2 344 (324)	22.0 (4.2)	5.1 (5.0)	0.73	b
		2006	Cahill	–	13 030 (1444)	23.8 (3.0)	5.4 (6.4)	0.78	a
			Rocker	–	3 809 (525)	18.0 (3.3)	4.3 (2.1)	0.73	b

*Within each location–year combination, means followed by the same lower case letters were not significantly different at $P \leq 0.05$ as determined by the test for individual and pooled residual sum of squares.

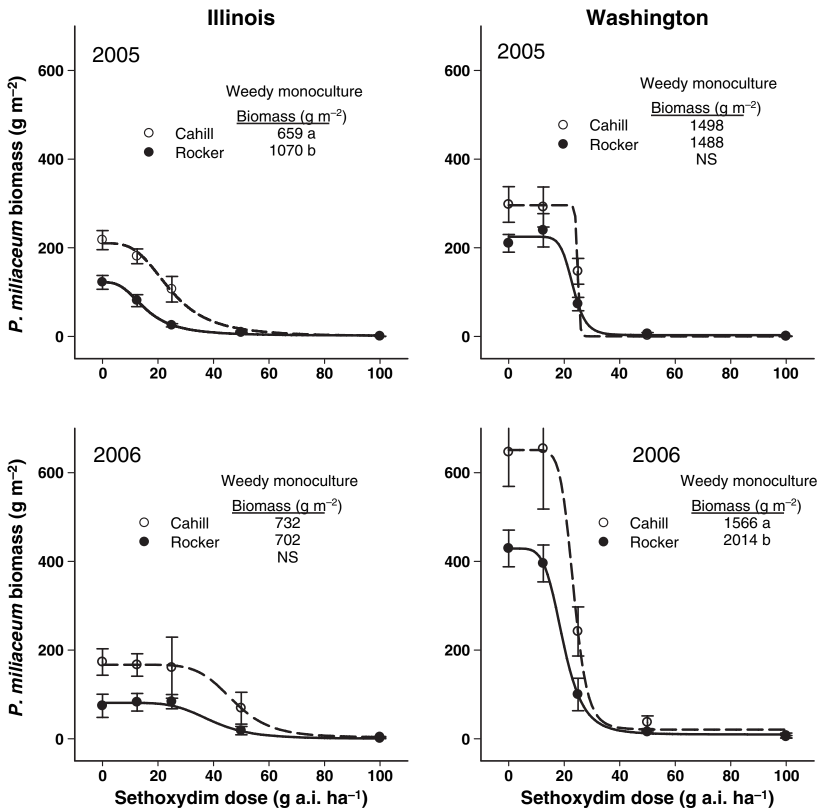

Fig. 1 *Panicum miliaceum* shoot biomass (g m^{-2}) as a function of sethoxydim dose in two sweet corn hybrids in Urbana, Illinois and Prosser, Washington. Standard error bars and fitted logistic Eqn 1 are included. *Panicum miliaceum* biomass in weedy monoculture plots is included, and means followed by different letters are different at $P \leq 0.05$.

variance in *P. miliaceum* biomass and fecundity at sub-lethal sethoxydim doses (e.g. below 50 g ha^{-1}) was lower in Rocker than Cahill (data not shown). Gunsolus and Buhler (1999) propose that farmer's perception of risk, variability inherent in agriculture, is the most limiting factor to adoption of integrated weed management. Our work reveals that risk can be lowered by farmers' choice of crop cultivar, as performance of the weed management system is directly influenced by the sweet corn hybrid.

Applying the relative potency concept (Ritz *et al.*, 2006) to these experiments provides additional evidence of differences in the hybrids' ability to suppress *P. miliaceum*. Relative potency (r) equal to 1 indicates that hybrids have a similar effect on the weed; however, relative potency greater than 1 (1.1–1.7) was observed under most conditions (Fig. 2). We infer that Cahill's suppressive ability needs to be supplemented to match the 'currency' of Rocker's suppressive ability. Moreover, relative potency tends to increase with weed biomass and fecundity, indicating that Rocker's advantage has even higher value when sethoxydim efficacy is poor (i.e. abundant weed biomass). This study demonstrates that season-long weed suppression involving sub-lethal herbicide dose is associated with the extent of crop competitive ability provided by sweet corn, which is not constant between the hybrids.

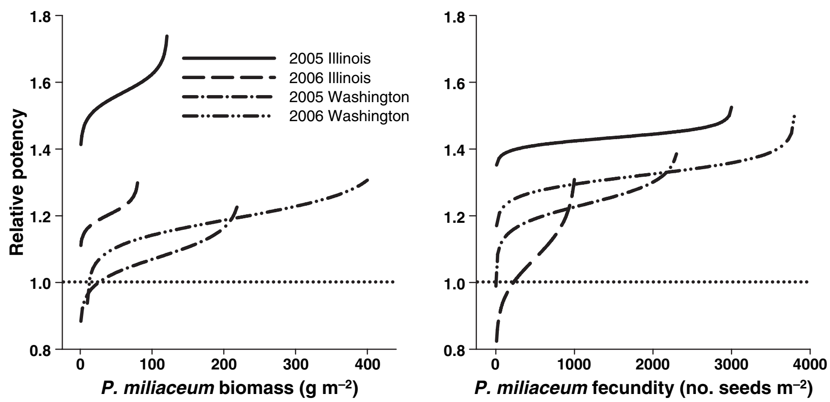

Fig. 2 Relative potency (r) of sweet corn hybrid Rocker, relative to Cahill, as a function of *Panicum miliaceum* biomass and fecundity. Dotted line indicates that the two hybrids are equally potent ($r = 1$), Cahill is more potent than Rocker below the dotted line ($r < 1$) and Rocker is more potent than Cahill above the dotted line ($r > 1$).

Table 4 Weed-free sweet corn yields

Location	Year	Hybrid	Weed-free yield* Ear mass (mt ha^{-1})	Ear number (boxes ha^{-1})	Husked mass (mt ha^{-1})	Kernel mass (kg ha^{-1})
Illinois	2005	Cahill	10.8 a	732 a	7.7 a	3.07 a
		Rocker	16.1 b	953 a	10.2 b	4.58 b
	2006	Cahill	14.6 a	1020 a	10.3 a	5.70 a
		Rocker	22.0 b	1390 b	14.9 b	8.23 b
Washington	2005	Cahill	17.4 a	1340 a	–	–
		Rocker	23.6 a	1360 a	–	–
	2006	Cahill	25.0 a	1580 a	–	–
		Rocker	25.1 a	1650 a	–	–

*Within each location–year combination, means followed by the same lower case letters were not significantly different at $P \leq 0.05$ as determined by a protected, Bonferroni-corrected multiple comparison procedure. Husked mass and kernel mass were measured in Illinois only.

Sweet corn yield

Weed-free yields varied with location, hybrid and yield trait. In Washington, no differences were detected between hybrids for ear mass and number (Table 4). Ear mass averaged 20.5 and 25.0 mt ha^{-1} and ear number averaged 1350 and 1620 boxes ha^{-1} in 2005 and 2006 respectively. In Illinois, Rocker ear mass yielded 16.1 and 22.0 mt ha^{-1} in 2005 and 2006, averaging 50% higher than Cahill (Table 4). Smaller differences in ear number were observed between hybrids. Husked and kernel mass also differed by hybrid, with Rocker yielding 32–49% more than Cahill. Recovery was similar between hybrids, averaging 28.4% in 2005 and 38.2% in 2006 (data not shown). Poorer weed-free yields in Illinois in 2005 were the result of hot, dry conditions as evidenced by the significant departure from 30 years of average precipitation and temperature (data not shown).

Weed suppression provided by sethoxydim dose improved sweet corn yield in three of the four site–years and in one case had an interaction effect with the hybrid (Table 5). In Washington in 2006, ear mass yield of Rocker was constant across sethoxydim dose, whereas reduced doses of sethoxydim resulted in lower ear mass yield of Cahill (Fig. 3). Otherwise, ear mass typically increased as sethoxydim dose increased, irrespective of the hybrid. Ear number, husked mass and kernel mass had similar responses to sethoxydim dose and hybrid (data not shown). Although weed-free yields were similar between hybrids in Washington, significant main effects and interaction effects with hybrids indicate that yield stability was poorer in Cahill at reduced sethoxydim doses.

Sweet corn yield loss as a result of weed interference varies among hybrids. Williams *et al.* (2008) quantified relative yield loss over a range of *P. miliaceum* densities for three hybrids differing in canopy density. In three of

Table 5 Significance (*P*) of hybrid, sethoxydim dose and their interaction on sweet corn yield when grown in the presence of *Panicum miliaceum**

Location	Year	Factor	*P* Ear mass	Ear number	Husked mass	Kernel mass
Illinois	2005	Hybrid	0.000	0.000	0.001	0.001
		Dose	0.000	0.000	0.000	0.001
		Hybrid * dose	0.230	0.055	0.183	0.517
	2006	Hybrid	0.000	0.000	0.004	0.058
		Dose	0.004	0.001	0.002	0.007
		Hybrid * dose	0.493	0.662	0.918	0.987
Washington	2005	Hybrid	0.006	0.038	–	–
		Dose	0.879	0.788	–	–
		Hybrid * dose	0.156	0.883	–	–
	2006	Hybrid	0.000	0.014	–	–
		Dose	0.000	0.007	–	–
		Hybrid * dose	0.027	0.224	–	–

*Husked mass and kernel mass were measured in Illinois only.

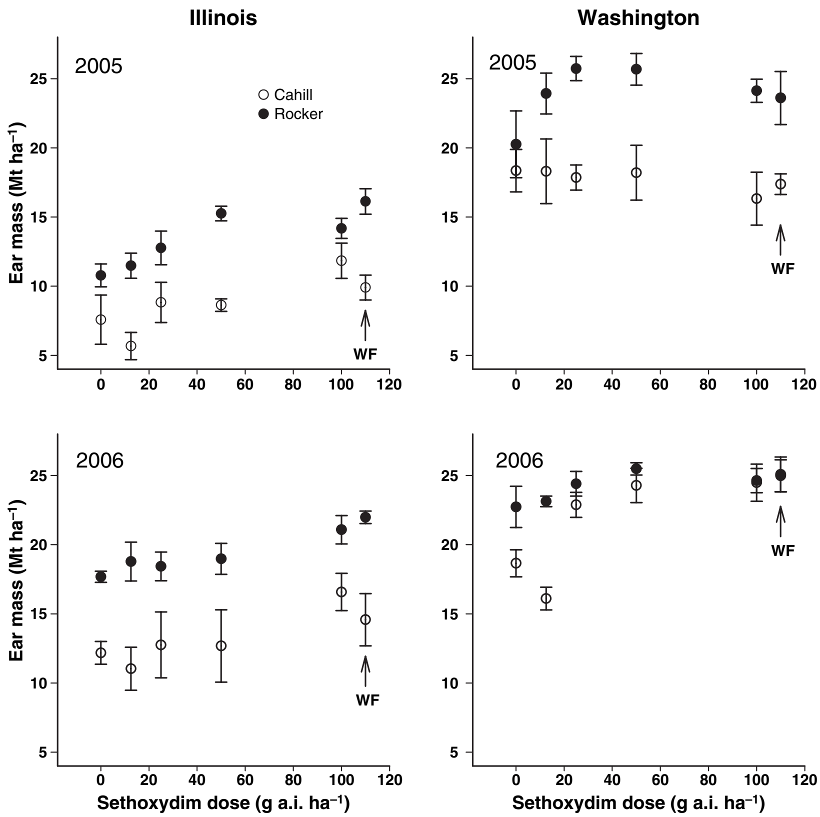

Fig. 3 Yield of ear mass (mt ha^{-1}) of two sethoxydim-tolerant sweet corn hybrids grown with *Panicum miliaceum* that had been treated with 0–100 g a.i. (active ingredient) per hectare. Field studies were conduced in Urbana, Illinois and Prosser, Washington in 2005 and 2006. Standard error bars and weed-free yields (WF) are included.

the four site–years, a less-dense canopy hybrid (Spirit) suffered higher relative ear mass losses than a denser canopy hybrid (WHT2801). Path analysis in the present work shows that sweet corn LAI and sethoxydim dose often had direct and indirect effects respectively, on crop yield. *Within-hybrid variation* in sweet corn LAI more frequently influenced crop yield than *P. miliaceum* biomass (Fig. 4, Table 6). Apparently LAI variation *within each hybrid* had a small influence on *P. miliaceum* growth, relative to variation in other model terms, but did contribute to the yield. One exception is Cahill in Washington, where LAI suppressed weed biomass and was negatively correlated with crop yield.

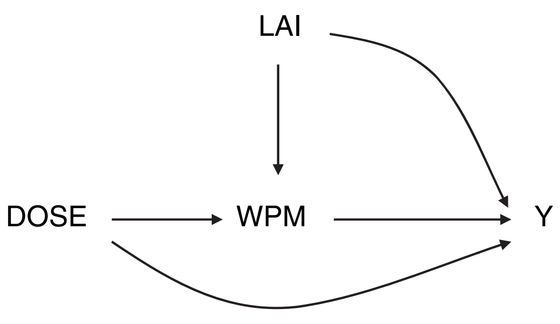

Fig. 4 Path analysis model for comparing sethoxydim dose (DOSE), crop leaf area index (LAI) and *Panicum miliaceum* biomass (WPM) contributions to sweet corn yield (*Y*).

Negative path coefficients for the effect of herbicide dose on *P. miliaceum* biomass ranged from –0.667 to –0.750, indicating the direct suppressiveness of sethoxydim. As expected of an herbicide-tolerant crop, no direct effects of herbicide dose were observed on crop yield. However, the indirect effects of herbicide dose on crop yield, mediated through *P. miliaceum* biomass reduction, were significant for all of the Cahill's yield traits, but not Rocker (Table 6). Apparently, the variation in *P. miliaceum* interference was important in the yield of Cahill only. This observation provides further evidence that crop competitive ability varies among hybrids, with a less competitive hybrid requiring relatively more weed suppression by the herbicide to maintain yield.

Previous studies have explored the use of crop competitive ability to improve weed management systems (Callaway, 1992; Jordan, 1993; Wang *et al.*, 2007). Several have demonstrated that competitive ability can be enhanced through genetic approaches, such as cultivar selection (Lemerle *et al.*, 2001) and breeding (Jannink *et al.*, 2000), or cultural approaches, such as crop row spacing (O'donovan *et al.*, 2006) and fertility management (Davis & Liebman, 2001). While crop competitive ability can make several small but cumulative contributions to weed suppression, competitive ability alone generally will not kill weeds outright and

Table 6 Standardised regression coefficients for path analysis of sethoxydim dose, crop leaf area index and *Panicum miliaceum* biomass contributions to yield of two sweet corn hybrids

Yield variable (*Y*)	Location	Hybrid	Standardised regression coefficients				
			DOSE → WPM	LAI → WPM	DOSE → *Y*	LAI → *Y*	WPM → *Y*
Ear mass	Illinois	Cahill	−0.750*	0.122	0.038	0.461*	−0.526*
		Rocker	−0.739*	−0.109	0.208	0.401*	−0.131
	Washington	Cahill	−0.667*	−0.360*	−0.210	−0.645*	−0.740*
		Rocker	−0.721*	0.211	0.013	0.118	−0.387
Ear number	Illinois	Cahill	−0.750*	0.122	0.035	0.463*	−0.521*
		Rocker	−0.739*	−0.109	0.158	0.496*	−0.094
	Washington	Cahill	−0.667*	−0.360*	−0.055	−0.067	−0.501*
		Rocker	−0.721*	0.211	−0.033	0.391*	−0.230
Husked mass	Illinois	Cahill	−0.750*	0.122	0.056	0.461*	−0.511*
		Rocker	−0.739*	−0.109	0.198	0.366*	−0.149
Kernel mass	Illinois	Cahill	−0.750*	0.122	0.019	0.575*	−0.377*
		Rocker	−0.739*	−0.109	0.159	0.365*	−0.124

The symbol * denotes standardised regression coefficients significant at the $P \leq 0.01$ level.
DOSE, sethoxydim dose (g ha^{-1}) applied at three- to four-leaf stage; LAI, leaf area index near crop anthesis; WPM, *P. miliaceum* biomass (g m^{-2}) measured at the time of sweet corn harvest; *Y*, sweet corn yield as ear mass (mt ha^{-1}), ear number (boxes ha^{-1}), husked mass (mt ha^{-1}) and kernel mass (kg ha^{-1}).

needs to be coupled with other types of management tactics. A growing consensus calls for research that identifies ecological processes that can be used to optimise integrated approaches to weed management (Thill *et al.*, 1991; Buhler, 2002).

This study demonstrates that under suboptimal conditions, herbicide performance throughout the season depends in large part on the extent of the crop competitive ability provided by sweet corn. Furthermore, sweet corn hybrids do not have the same effect on suppressing persistent weeds or tolerating their presence. The two hybrids in this study performed consistently under a wide range of environmental conditions, suggesting that these results may have s broad application to North American sweet corn production. If weed management systems have been developed in the context of competitive hybrids such as Rocker, then these results may shed light on variable weed control in sweet corn. Less competitive hybrids would have more weed growth, seed production and crop losses when herbicides are not completely effective. Study of the interaction of competitive ability with other forms of weed management may provide greater practical insight than the investigation of competitive ability alone.

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