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Control of Both Winter Annual and Summer Annual Weeds in No-Till Corn with Between-Row Mowing Systems

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In previous research, summer annual weeds were successfully controlled in no-till corn with between-row mowing systems that consisted of soil-residual preemergence herbicides banded over corn rows followed by mowing weeds close to the soil surface one or two times later during the growing season. The objective of this research was to determine whether between-row mowing systems could successfully control both winter annual and summer annual weeds as well as broadcast herbicides perform in no-till corn. In two of three years in Missouri, between-row mowing systems controlled and reduced both winter annual and summer annual weed cover and prevented weeds from reducing corn yields. Corn yields for the following no-till weed management systems equaled the weed-free check: winter annual weed control with between-row mowing plus preplant, banded, postemergence-applied glyphosate at 1.1 kg ae/ha and later summer annual weed control with postplant, banded, preemergence-applied atrazine plus S-metolachlor at 2.2 plus 1.8 kg ai/ha followed by between-row mowing. Winter annual weeds growing between rows were controlled with one mowing, and later summer annual weeds were controlled with either one late or "middle" mowing or two mowings (i.e., early and late). Total herbicide use was reduced 50% (i.e., 25 and 25%, respectively) in no-till corn. Commercially acceptable corn stands were needed for between-row mowing systems to adequately control weeds. In one of three years when corn stands were half of those of the other two years, broadcast herbicides performed better than between-row mowing systems in no-till corn.

Nomenclature: Atrazine; S-metolachlor; corn, *Zea mays* L. 'Pioneer 33G28' ZEAMX.

Key words: Alternative weed control, application, banding, band application, cutting, mechanical weed control, nonchemical weed control, decreased herbicide rate.

In 2002, U.S. farmers treated 89% of corn hectareage with herbicides to control weeds; 62% was treated with one herbicide, atrazine (USDA-NASS 2004). To address environmental problems (Logan 1993; Richards and Baker 1993) and economic concerns, weed scientists continue to explore ways to reduce herbicide use in extensively grown field crops (Bicki et al. 1991; Doyle and Stypa 2004; Kudsk and Streibig 2003; Zhang et al. 2000). Herbicide use can be reduced by: (1) reducing herbicide rates and changing application timing, (2) substituting different herbicides that are applied at lower rates, or (3) decreasing the area treated with herbicides and substituting mechanical weed control methods. This research focused on the third tactic which concerned substituting unconventional mechanical weed control methods for herbicides.

Published research on no-till corn and soybean [*Glycine max* (L.) Merr.] showed that preemergence herbicide use for summer annual weed control could be reduced 50% by banding herbicides over crop rows and substituting between-row mowing for herbicides (Donald 2000a, 2000b; Donald et al. 2001). This equaled a 50% reduction in preemergence herbicide use and a 25% reduction in total herbicide use in no-till. In corn and soybean, crop yields were statistically indistinguishable among weed-free checks, broadcast preemergence herbicide treatments, and some treatments using banded preemergence herbicide followed by between-row mowing. Unlike conventional cultivation, banded preemergence herbicide followed by between-row mowing was compatible with no-till farming (Donald et al. 2001). Two properly timed between-row mowings, close to the soil surface before crop canopy closure, killed common emerged summer annual weeds, such as giant foxtail [*Setaria faberi* Herrm. SETFA], common ragweed (*Ambrosia artemisiifolia* L. AMBEL), and common waterhemp (common waterhemp, *Amaranthus rudis* Sauer AMATA).

A successful between-row mowing system for controlling both winter annual and summer annual weeds could reduce herbicide use 50% in no-till corn compared with either broadcast-applied postemergence glyphosate for winter annual weed control or broadcast-applied preemergence herbicides, such as atrazine plus S-metolachlor, for summer annual weed control. The research objective was to determine whether between-row mowing systems could successfully substitute for broadcast-applied herbicides in no-till corn by reducing weed cover and preventing yield losses. Alternative weed management systems were optimized for two winter annual weed control treatments and four summer annual weed control treatments and consisted of broadcast herbicides vs. banded herbicide over corn rows followed by between-row mowing once or twice close to the soil surface (Tables 1 and 2). One null hypothesis was that control of winter annual weeds following broadcast-applied glyphosate (WA Glyphosate) would be indistinguishable from between-row mowing systems (WA Mow) before no-till corn planting. The second null hypothesis was that control of summer annual weeds with broadcast-applied preemergence atrazine plus S-metolachlor (SA Broadcast) would be indistinguishable from between-row mowing systems (SA Mow 1× Middle, SA Mow 1× Late, SA Mow 2×) for summer annual weed control in no-till corn. The third null hypothesis was that between-row mowing systems with either one or two mowings would control

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Table 1. Treatment sequences were designed to control winter annual weeds before controlling summer annual weeds in no-till corn. In the table, herbicides were "broadcast" when both in-row and between-row positions were treated. Between-row mowing systems consisted of herbicides banded over crop rows and mowing emerged weeds close to the soil surface between rows. Relative times of mowing are summarized in Table 3 and Figure 2.

Treatment no.	Winter annual weed control before planting		Summer annual weed control after crop planting				Reduction in herbicide use relative to treatment no. 3
	Postemergence		Preemergence followed by		Postemergence		
	In-row	Between-row	In-row	Between-row	In-row	Between-row	
							%
1	Glyphosate	Glyphosate	Weedy check				—
2	Glyphosate	Glyphosate	Weed-free check				—
3	Glyphosate	Glyphosate	Atrazine plus S-metolachlor	Atrazine plus S-metolachlor	None	None	0
4	Glyphosate	Glyphosate	Atrazine plus S-metolachlor	None	None	Mow 1× early-middle (Table 3 and Figures 1 to 2)	25
5	Glyphosate	Glyphosate	Atrazine plus S-metolachlor	None	None	Mow 1× Late (Table 3 and Figures 1 to 2)	25
6	Glyphosate	Glyphosate	Atrazine plus S-metolachlor	None	None	Mow 2× early and late (Table 3 and Figures 1 to 2)	25
7	Glyphosate	Mow 1×	Weedy check				—
8	Glyphosate	Mow 1×	Weed-free check				—
9	Glyphosate	Mow 1×	Atrazine plus S-metolachlor	Atrazine plus S- metolachlor	None	None	25
10	Glyphosate	Mow 1×	Atrazine plus S- metolachlor	None	None	Mow 1× early-middle (Table 3 and Figures 1 to 2)	50
11	Glyphosate	Mow 1×	Atrazine plus S- metolachlor	None	None	Mow 1× Late (Table 3 and Figures 1 to 2)	50
12	Glyphosate	Mow 1×	Atrazine plus *S*- metolachlor	None	None	Mow 2× early and late (Table 3 and Figures 1 to 2)	50

summer annual weed cover the same. Alternative hypotheses were that, following treatment, corn yields would be ranked: weed-free check = broadcast-applied herbicide > between-row mowing twice ≥ between-row mowing once > weedy check. For between-row weed cover, the rank order would be reversed.

Table 2. Abbreviations for no-till winter annual weed control treatments described in Table 1.

Treatment no.	Treatment abbreviations	
	Winter annual (WA) weed control treatment (N = 2)	Summer annual (SA) weed control treatments (N = 6)
1	WA Glyphosate (1)	SA Weedy (1)
2	WA Glyphosate (1)	SA Weed-free (2)
3	WA Glyphosate (1)	SA Broadcast (3)
4	WA Glyphosate (1)	SA Mow 1× Middle (4)
5	WA Glyphosate (1)	SA Mow 1× Late (5)
6	WA Glyphosate (1)	SA Mow 2× (6)
7	WA Mow (2)	SA Weedy (1)
8	WA Mow (2)	SA Weed-free (2)
9	WA Mow (2)	SA Broadcast (3)
10	WA Mow (2)	SA Mow 1× Middle (4)
11	WA Mow (2)	SA Mow 1× Late (5)
12	WA Mow (2)	SA Mow 2× (6)

Materials and Methods

Site, Weather, and Weeds. In 2001, 2002, and 2003, no-till corn was planted after no-till soybeans at the University of Missouri's Bradford Research and Extension Center in north-central Missouri near Columbia (38°53′43.5″N, 92°12′37.9″W, 269 m altitude). The soil was a Mexico silty clay loam (fine, smectitic, mesic Aeric Vertic Epiaqualfs) that had 18% sand, 48% silt, 34% clay, 3.3% organic matter, and pH values of 5.5 to 5.8. According to the soil testing lab at the University of Missouri, Columbia, soil pH was the salt pH, and values ran approximately 0.5 units lower than customary water pH values.

Historical weather data through 2003 were collected at Bradford (Figure 1). However, 1995 data from nearby Sanborn Experimental Field and 2001 data from the University of Missouri South Farm were substituted in 1995 and 2001, because weather data in those years were incomplete at Bradford. Daily heat units were defined as [(maximum temperature − minimum temperature)/2 − base temperature] in degree C days. Heat sums were calculated by summing daily heat units from corn planting until harvest using a base temperature of 10 C (Ruiz et al. 1998).

Shepherdpurse [*Capsella bursa-pastoris* (L.) Medik. CAPBP], fleabane species (*Erigeron* spp.), and horseweed [*Conyza canadensis* (L.) Cronq. ERICA] were the major winter annual weeds present. Curly dock (*Rumex crispus* L. RUMCR)

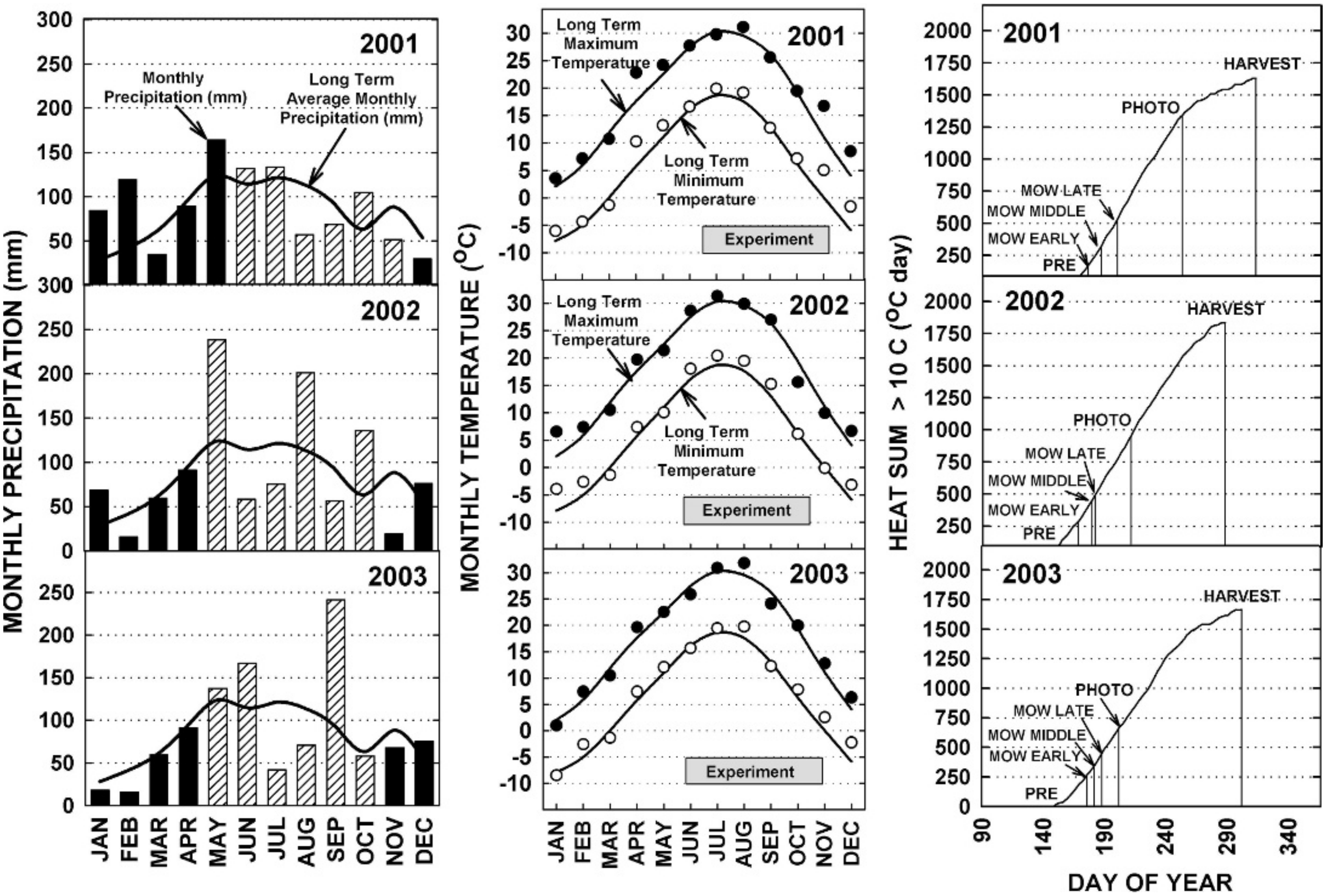

Figure 1. The monthly precipitation (bars) and long-term average monthly precipitation (lines) vs. month of the year from 2001 to 2003 (left panels). Monthly average maximum and minimum air temperatures (solid and open circles, respectively) and long-term averages (lines) vs. month of the year (middle panels). Cumulative heat sums > 10 C (i.e., growing degree days) after planting vs. day of the year (right panels). The 9-yr averages were from 1993 to 2001. The length of the experiments was indicated by either hatched bars (left panels) or a horizontal bar "Experiment" (middle panels). Abbreviations: PRE, preemergence herbicides applied; MOW, between-row mowing imposed; PHOTO, photographs taken.

was minor and scattered. The summer annual weeds giant ragweed (*Ambrosia trifida* L. AMBTR) and common ragweed had emerged when winter annual weeds were sprayed.

Giant foxtail was the major summer annual grass weed present. After giant foxtail, most remaining weed cover consisted of the following summer annual broadleaf weeds: common waterhemp and prickly sida (*Sida spinosa* L. SIDSP). Shattercane [*Sorghum bicolor* (L.) Moench SORVU] and ivyleaf morningglory [*Ipomoea hederacea* (L.) Jacq. IPOHE] were present, minor, and scattered.

Agronomic Practices. Based on soil tests and recommendations of the University of Missouri soil testing lab, corn was fertilized with N–P–K for grain yield goals of 8,790, 8,790, and 9,420 kg/ha in 2001, 2002, and 2003, respectively. Before or at no-till planting, N–P–K was banded 4 cm deep at 213–112–112, 169–0–0, and 218–123–123 kg/ha, respectively, with a no-till grain drill[1] (Table 1). In 2001, 2002, and 2003, glufosinate-resistant 'Pioneer 33G28' corn seed was planted[2] 4 to 5 cm deep in 76-cm rows at 79,840, 79,910, and 81,520 seeds/ha, respectively. Glufosinate-resistant seed was used in order to facilitate creation of weed-free checks. Seeds were treated with fludioxonil and metalaxyl-m.

Treatments. The 12 treatments were no-till weed management systems that consisted of all combinations of sequences of two treatments for controlling winter annual weeds and four subsequent treatments for controlling summer annual weeds (Tables 1 to 3 and Figure 1). Treatment abbreviations are summarized (Table 2 and the top of Figures 3 to 5). Two alternative treatments for controlling winter annual weeds (WA Glyphosate vs. WA Mow) were followed by four different experimental treatments for controlling summer annual weeds (SA Broadcast, SA Mow 1× Early, SA Mow 1× Late, and SA Mow 2×) and two checks (SA Weedy and SA Weed-free). Treated plots measured 3 m by 9.1 m.

Broadcast Herbicides for Winter Annual Weed Control. Glyphosate plus ammonium sulfate at 1.1 kg ae/ha plus 3.4 kg/ha, respectively, was broadcast-applied to prepare a no-till seedbed (Tables 1 to 3; WA Glyphosate). In 2001, 2002, and 2003, a tractor-mounted sprayer was operated at 207 kPa and speeds of 2.4, 4.8, and 5 km/h, respectively. In these three

Table 3. Dates for field operations, treatments, or measurements.[a]

Field operations, treatments or measurements	2001 Date	2001 DAP	2002 Date	2002 DAP	2003 Date	2003 DAP
Control winter annual weeds						
Brush hog winter annual weeds	June 11	—	—	—	—	—
Mow winter annual weeds between rows	June 12	—	May 22	—	May 23	—
Broadcast or band glyphosate over rows	June 12	—	May 22	—	May 27	—
Apply N–P–K fertilizer into soil with no-till planter	June 11	—	April 25	—	May 29	—
Plant corn	June 12	—	May 22	—	May 29	—
Broadcast treatment: atrazine plus S-metolachlor or band treatment: atrazine plus S-metolachlor with between-row mowing (see below)	June 12	0	May 23	1	May 30	1
Corn emerges	June 16	4	May 30	8	June 7	9
Measure corn stand	June 29	17	June 27	37	June 18	20
Mow weeds between rows						
2× Treatment: Mow small weeds for first time	June 25	13	June 17	26	June 25	27
Mow weed regrowth again	July 6	24	July 1	40	July 7	39
1× Treatment: Mow medium weeds only once	July 6	24	June 28	37	July 1	33
1× Treatment: Mow large weeds only once	July 19	37	July 1	40	July 7	39
Control weeds in weed-free checks:						
Apply glufosinate	June 22	10	—	—	June 26	29
Apply glufosinate	—	—	—	—	July 18	50
Hoe and hand pull weeds	July 6	24	June 17	27	June 25	27
Hoe and hand pull weeds again	July 19	37	July 1	40	—	
Hoe and hand pull weeds again	—	—	July 10	49	—	—
Hoe and hand pull weeds again	—	—	July 18	57	—	—
Hoe and hand pull weeds again	—	—	August 12	82	—	—
Photograph weed cover	September 10	90	July 30	69	July 21	53
Harvest corn	November 9	150	October 15	146	October 29	153

[a] Abbreviation: DAP, days after planting.

years, spray volumes of 159, 84, and 76 L/ha water were applied, respectively. In 2001, 2002, and 2003, flat fan nozzle tips[3] were spaced 51, 76, and 76 cm apart on the spray boom, respectively. In these three years, the boom was held about 60, 85, and 85 cm above the soil surface, respectively.

Banded Herbicides for Winter Annual Weed Control. For between-row mowing treatments, glyphosate at 1.1 kg ae/ha plus ammonium sulfate at 3.4 kg/ha was band-applied in 38-cm bands over 76-cm rows (Tables 1 to 3; WA Mow). In 2001, 2002, and 2003, a backpack sprayer was operated at 2.4, 2.4, and 3.5 km/h, respectively, at 207 kPA to apply spray volumes of 110, 110, and 72 L/ha water, respectively. Even nozzle tips[4] were spaced 76 cm on the boom, which was held about 53 cm above the soil surface.

Broadcast Herbicides for Summer Annual Weed Control. For summer annual weed control, preemergence atrazine plus S-metolachlor at 2.2 plus 1.8 kg ai/ha was broadcast-applied (Tables 1 to 3; SA Broadcast). In 2001, 2002, and 2003, a backpack sprayer was operated at 4.8, 4.8, and 5.0 km/h, respectively, using compressed CO_2 at 207 kPA to apply spray volumes of 84, 84, and 76 L/ha water. Flat fan nozzle tips were spaced 76 cm on the boom, and in 2001, 2002, and 2003 the boom heights were about 61, 84, and 84 cm, respectively.

Banded Herbicides for Summer Annual Weed Control. For between-row mowing treatments, preemergence atrazine plus S-metolachlor at 2.2 plus 1.8 kg ai/ha was band-applied in 38-cm-wide bands over 76-cm corn rows (Tables 1 to 3; SA Mow 1× Early, SA Mow 1× Late, and SA Mow 2×). In 2001, 2002, and 2003, a backpack sprayer was operated at 2.4, 2.4, and 3.5 km/h, respectively, using compressed CO_2 at 207 kPA to apply spray volumes of 110, 110, and 72 L/ha water, respectively. Even nozzle tips were spaced 76 cm apart on the boom, and the boom height was about 53 cm.

Between-Row Mowing. A plastic cord mower[5] was used to mow weeds growing between rows close to the soil surface (i.e., about 3 cm above the surface) (Tables 1 to 3: WA Mow and SA Mow 1× Middle, SA Mow 1× Late, and SA Mow 2×). The mowing width was 60 cm, leaving about 8 cm unmowed on either side of corn rows that were spaced 76 cm apart. Weeds growing in rows were controlled with band-applied preemergence herbicides (see above). Consequently, the mowed zone between rows slightly overlapped the outer edges of the herbicide bands over rows. Herbicides banded over rows had completely controlled weeds by the time that weeds were first mowed between rows (Table 3 and Figure 1). Weeds were mowed either twice ("early" followed by "late") or once ("middle" or late). Corn and summer annual weed heights for these relative times differed slightly among years (Figure 2, SA Mow 1× Middle, SA Mow 1× Late, and SA Mow 2×)

Weed-Free and Weedy Checks. For both winter annual weed control treatments, the experiment included additional weedy and weed-free checks (Tables 1 to 3; SA Weedy and SA Weed-free). In weedy checks, winter annual weeds were controlled, but summer annual weeds were uncontrolled. "Weed-free" checks were sprayed with glufosinate at 0.28 kg ae/ha and shallowly hoed between and in rows, and in-row weeds were hand pulled several times during the growing season until corn silking and canopy closure. To avoid root

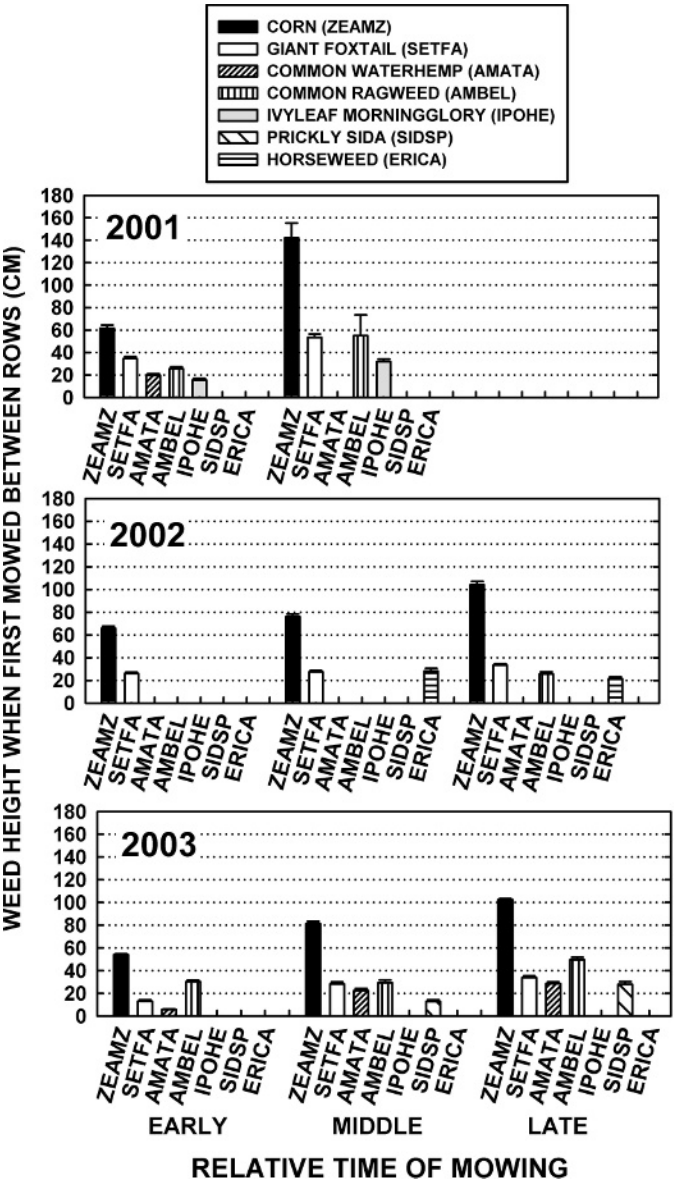

Figure 2. Corn and weed heights (cm, means ± standard error) when weeds growing between rows were first mowed vs. relatives times of mowing in 2001 to 2003. Measurements were not taken for the ''late'' time in 2001.

pruning and yield loss, hoeing was shallow and close to the soil surface. To avoid yield losses by breaking corn leaves and trampling during weeding, hoeing was ended in midsummer. Although these ''hand-weeded'' plots were not completely weed-free by harvest, weeds emerging after silking and canopy closure were stunted and did not reduce corn grain yields (Bedmar et al. 1999; Hall et al. 1992).

Measurements. At midseason, total weed control was visually evaluated based on a scale of 0% (no control) to 100% (complete kill) (Table 3). After cutting borders at either end of all plots, corn was combine harvested from the two center rows of four-row plots in an area measuring 1.5 by 8.2 m in 2001 and 2002 and 1.5 by 7.6 m in 2003. Grain yields were adjusted to 15% moisture content.

Projected between-row weed ground cover from photographs was used to measure treatment effectiveness (Table 3 and Figure 1). Projected ground covers of between-row grass, broadleaf, and total weeds (i.e., grass plus broadleaf weeds), but not crop cover, were measured from digital photographs[6] taken between rows and in corn rows. Corn foliage overhanging and obscuring the between-row region was pulled back with 1 m^2 wooden frame panels covered with black cloth, and an orange dowel was extended at 90° 19 cm out from the crop row just above the soil surface toward the row middle to mark the herbicide band width in photographs. Before taking photographs in 2002 and 2003, in-row and between-row weed cover were separated from one another using black panels extended to the soil surface to prevent foliage overhanging from adjacent zones from obscuring in-row and between-row weed cover. Four photographs per zone per plot were taken vertically (i.e., camera facing toward the soil surface) with a digital camera at a height of 47 cm. Each photograph corresponded to 1.1 m^2 at the soil surface based on photographs of a 30- by 30-cm orange calibration plate. For each photograph, the maximum weed canopy height from the soil surface also was measured to the nearest 0.5 cm against a measuring rod. Image analysis software[7] was used to crop between-row and in-row zones and automatically superimpose a 20- by 20-pixel grid over each cropped photograph. Total weed cover was calculated as a percentage of the number of grid intersections covered by grass or broadleaf weeds divided by the total number of grid interactions per photograph. Weed cover measurements were the average of four between-row or in-row photographs per plot.

In 2002 and 2003, the photographed surface was shaded under an umbrella to minimize contrast between brightly lit and heavily shaded spots and ensure uniform diffuse light intensity for all photographs taken on one day. This allowed total weed cover to be determined using the software's automated measurement capacity to distinguish green from other colors. Total weed cover (%) was calculated as the ratio of green pixels to total pixels per photograph × 100. In both years, total weed cover measurements are the average of four between-row or in-row photographs per plot. Using 2002 data, projected total weed cover determined by visual grid point-intersection counting (Y) was regressed vs. projected total weed cover determined by automated green pixel counting (X), and the regression equations (coefficient ± standard error) were

$$Y = 0.36\ (\pm\ 0.73) + 1.07\ (\pm\ 0.02) \times X, \quad \text{for between-row cover } (r^2 = 0.99) \qquad [1]$$

$$Y = -0.11\ (\pm\ 1.92) + 1.11\ (\pm\ 0.04) \times X, \quad \text{for in-row cover } (r^2 = 0.97) \qquad [2]$$

Thus, weed cover determined by automated green pixel counting using software[3] was linearly related to weed cover determined by visual grid point-intersection counting, with an X intercept of 0 and a slope near 1.

Statistical Analysis. The experiment used a randomized complete block design with four, five, and five blocks in 2001, 2002, and 2003, respectively. Blocking was based on weed ground cover observed in preceding years (Hoshmand 1994). Corn yields, in-row and between-row weed cover, and in-row and between-row maximum weed canopy height were subjected to ANOVA using statistical software.[8] Means were separated by Fisher's protected LSD test at P = 0.05.

Results and Discussion

Corn Yields. In the weed-free checks that received broadcast glyphosate for controlling winter annual weeds (WA Glyphosate SA Weed-free), no-till corn yields were 30, 106, and 68% of the yield goals for which the experiment was fertilized in 2001, 2002, and 2003, respectively (Figures 3 to 5). For the weed-free checks that received glyphosate banded over rows plus between-row mowing for winter annual weed control (WA Mow SA Weed-free), the corn yields were 66, 111, and 62% of yield goals in the three respective years.

Differences in weed-free yields among years were likely related to differences in seasonal rainfall (Figure 1), rather than no-till corn stands (Figures 3 to 5). It is well established that corn yields are highly sensitive to variable and low corn stands (Tokatlidis and Koutroubas 2004; Tollenaar 1992; Tollenaar et al. 1994b). Planned seeding densities varied slightly among years and were 78,840, 79,910, and 81,520 seed/ha in 2001, 2002, and 2003, respectively. However, established stands in 2002 were about half of those in 2001 and 2003 (Figures 3 to 5). The reasons for low stand establishment are unknown but likely result from an interaction between planter type (i.e., a different, modified planter was used in 2002), high crop residues, and dry hard soil at planting in 2002. Nevertheless, differences in corn stand among years were unrelated to relative differences in weed-free corn yields among years in this study (Figures 3 to 5).

Differences in weed-free corn yields among years were related to differences in seasonal midsummer rainfall during pollination, silking, and early seed-set in July and August (Figures 1 and 3 to 5). Weed-free yields were reduced in 2001 and 2003, and rainfall was below average in August and September of 2001 and in July and August of 2003. Slightly above-average maximum and minimum air temperatures (i.e., during day and night, respectively) may have interacted with below-average rainfall during critical silking, pollination, and early seed set stages to stress corn (Tollenaar and Wu 1999; Tollenaar et al. 1994a), limiting weed-free no-till corn yields in 2001 and 2003. In 2002, July rainfall was above average, and corn achieved the weed-free yield goal for which it was fertilized even though stands were half of those in the other two years.

The contribution of treatments for winter annual weed control to yields of SA Weedy and SA Weed-free treatments was examined in separate two-way ANOVA for each year (Table 4). The main effects of winter annual weed control on corn yields were different in 2001 (P = 0.05 or less), but not in the other two years (Table 4, WA Glyphosate vs. WA Mow). In addition, all interactions between treatments for

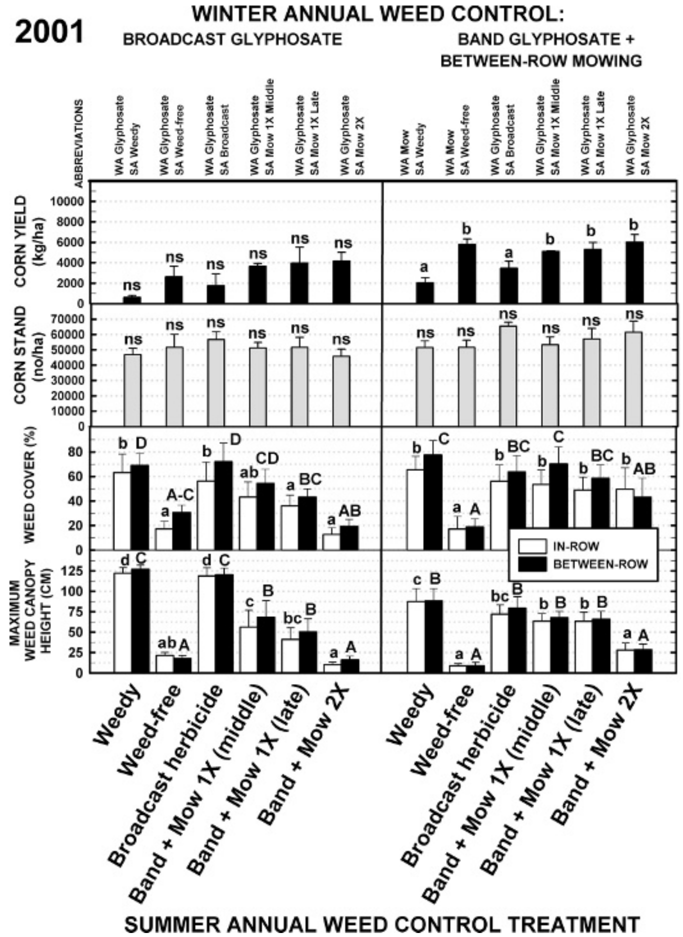

Figure 3. Corn grain yield (kg/ha), corn stand (no/ha), in-row and between-row weed cover (%) measured from photographs, and maximum in-row and between-row weed canopy height (cm) vs. weed management treatments for 2001. Winter-annual and summer-annual weed control treatments were indicated at the top and bottom, respectively. For each winter annual weed control treatment separately, means (± standard errors) were presented, and those means for each variable followed by the same letter (different fonts or cases for different variables separately) were not different at P = 0.05 by Fisher's protected LSD. Abbreviations: see Table 2; ns, nonsignificant.

winter annual and summer annual weed control were nonsignificant (P = 0.05).

Separate ANOVAs were conducted to compare only weed-free and weedy treatments. In all years in the weedy checks, annual weeds greatly reduced corn yields (WA Glyphosate SA Weedy vs. WA Glyphosate SA Weed-free and WA Mow SA Weedy vs. WA Mow vs. SA Weed-free) (Figures 3 to 5). After winter annual weeds were controlled with broadcast glyphosate, yields of weedy and weed-free treatments were statistically indistinguishable in 2001 (WA Glyphosate SA Weedy vs. WA Glyphosate SA Weed-free) (Figure 3). However, after winter annual weeds were controlled with glyphosate banded over rows plus between-row mowing in 2001 (WA Mow SA Weedy vs. WA Mow SA Weed-free), differences between weed-free and weedy checks were significant, and the yield of the weedy check was 35% of the weed-free yield. Likewise, when treatments for winter

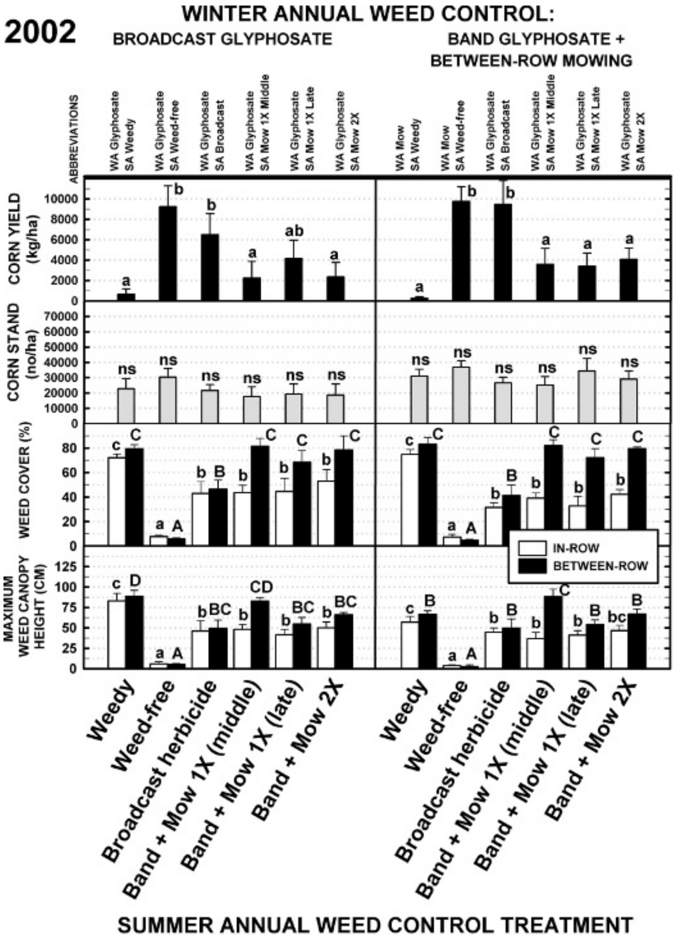

Figure 4. Corn grain yield (kg/ha), corn stand (no/ha), in-row and between-row weed cover (%) measured from photographs, and maximum in-row and between-row weed canopy height (cm) vs. weed management treatments for 2002. Winter-annual and summer-annual weed control treatments were indicated at the top and bottom, respectively. Under each winter annual weed control treatment separately, means (± standard errors) were presented, and those means for each variable followed by the same letter (different fonts or cases for different variables separately) were not different at P = 0.05 by Fisher's protected LSD. Abbreviations: see Table 2; ns, nonsignificant.

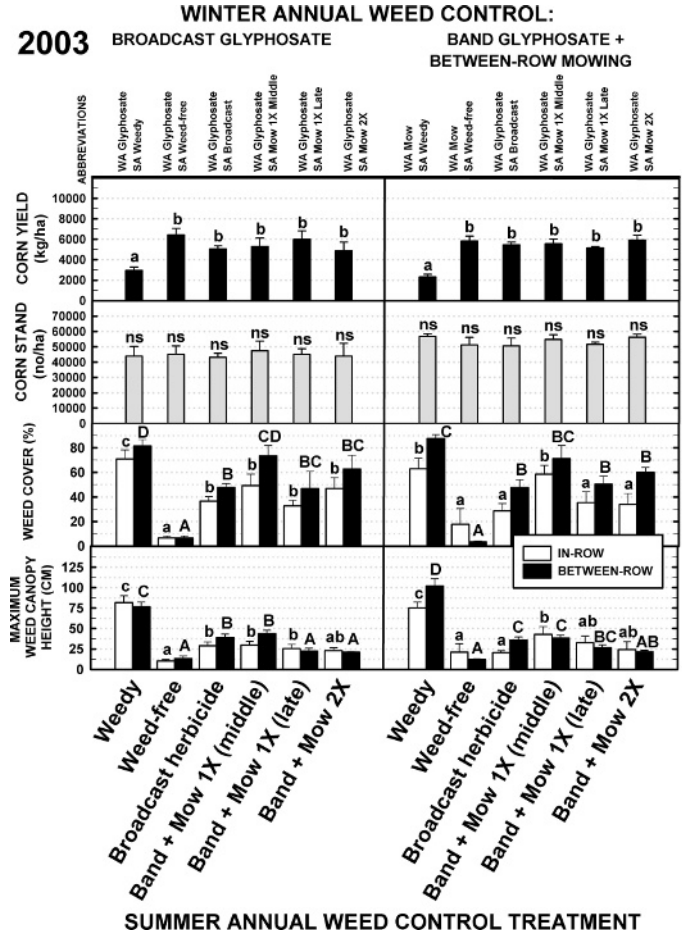

Figure 5. Corn grain yield (kg/ha), corn stand (no/ha), in-row and between-row weed cover (%) measured from photographs, and maximum in-row and between-row weed canopy height (cm) vs. weed management treatments for 2003. Winter-annual and summer-annual weed control treatments were indicated at the top and bottom, respectively. Under each winter annual weed control treatment separately, means (± standard errors) were presented, and those means for each variable followed by the same letter (different fonts or cases for different variables separately) were not different at P = 0.05 by Fisher's protected LSD. Abbreviations: see Table 2; ns, nonsignificant.

annual weed control (WA Glyphosate and WA Mow) were averaged, weeds reduced the yields of the weedy checks to 4.8 and 42.8% of the weed-free checks in 2002 and 2003, respectively.

In two of three years (2002 and 2003), there were no differences in corn yields that could be attributed to either of the two winter annual weed control treatments (WA Glyphosate vs. WA Mow) (Table 4 and Figures 3 to 5). The winter annual weed control treatment influenced subsequent corn yields with summer annual treatments in only one year (2001). Moreover, in all three years, interactions between treatments for winter annual and summer annual weed control were nonsignificant (Table 4). In all three years, banding glyphosate over rows and mowing weeds between rows controlled winter annual weeds (WA Mow) as well as broadcast-applied herbicide (WA Glyphosate) (Figures 3 to 5) and also reduced total herbicide use 25% for controlling winter annual weeds before planting no-till corn.

In all three years, the corn yields of the three between-row mowing systems for controlling summer annual weeds (SA Mow 1× Middle, SA Mow 1× Late, and SA Mow 2×) were statistically indistinguishable from each other (Figures 3 to 5). In two of three years (2001 and 2003), yields of these three treatments exceeded the weedy check (SA Weedy) and were indistinguishable from the weed-free check (SA Weed-free). In these three between-row mowing systems, there was no yield advantage to mowing summer annual weeds more than once. In 2001 and 2003, yields of the three between-row mowing systems for summer annual weed control also either equaled or exceeded the broadcast herbicide treatment (SA Broadcast). In one year (2002), the yield of the weed-free check was greater than the same three between-row mowing systems that, in turn, were all indistinguishable from the weedy check. In 2002 when corn stands were reduced to about half of the stand densities in 2001 and 2003, yields of between-row mowing systems were less than both the weed-

Table 4. ANOVA for corn yield.

Year	Source		df	Mean square	F	Significance
2001	Winter annual weed control	Hypothesis	1	40,613,033	19.58	0.000
	Summer annual weed control	Hypothesis	5	16,617,532	8.01	0.000
	Block	Hypothesis	3	11,675,950	5.63	0.003
	Interaction of winter and summer annual weed control	Hypothesis	5	965,158	0.47	0.799
		Error	33	2,074,459		
2002	Winter annual weed control	Hypothesis	1	12,260,591	1.30	0.260
	Summer annual weed control	Hypothesis	5	116,042,811	12.31	0.000
	Block	Hypothesis	3	42,203,251	4.48	0.004
	Interaction of winter and summer annual weed control	Hypothesis	5	4,786,425	0.51	0.769
		Error	44	9,427,984		
2003	Winter annual weed control	Hypothesis	1	79,534	0.06	0.802
	Summer annual weed control	Hypothesis	5	15,252,236	12.26	0.000
	Block	Hypothesis	3	3,012,252	2.42	0.063
	Interaction of winter and summer annual weed control	Hypothesis	5	1,368,991	1.10	0.374
		Error	44	1,244,561		

free check and broadcast herbicide treatment. Apparently, more normal corn stands and corn competition greatly contributed to the success of between-row mowing systems in 2001 and 2003.

Total Weed Cover and Maximum Weed Canopy Height. In all three years for both between-row and in-row total weed cover and maximum weed canopy height, values for the weedy checks (SA Weedy) were much greater than the weed-free checks (SA Weed-free) (Figures 3 to 5). In the weedy checks in 2001, values of in-row giant foxtail and broadleaf weed cover were 34 and 28% (total weed cover = 62%), respectively, whereas for between-row giant foxtail and broadleaf weed cover, they were 42 and 28% (total weed cover = 70%), respectively. In weedy checks in 2002 and 2003, values for total weed cover were greater than in 2001 and were mostly giant foxtail. In weedy checks in 2002, values for in-row and between-row giant foxtail cover were 83% (total weed cover = 85%) and 86% (total weed cover = 95%), respectively, and in 2003, they were 79% (total = 83%) and 77% (total weed cover = 89%), respectively.

In all three years in weedy checks, in-row total weed cover was less than between-row total weed cover, presumably because corn foliage overhanging the in-row zone shaded weeds earlier and more completely than between rows. In 2001, 2002, and 2003, values for in-row total weed cover were 64, 73, and 67%, respectively, whereas for between-row total weed cover, they were 74, 81, and 85%, respectively (Figures 3 to 5). Except for the weed-free checks (SA Weed-free), between-row total weed cover tended to exceed in-row total weed cover for most treatments (SA Broadcast, SA Mow 1× Middle or Late, SA Mow 2×), although this was not tested statistically. In weed-free checks, hoeing and hand weeding prevented in-row and between-row total weed cover from becoming different from each other by late in the growing season.

Two factors complicate discussion of the response of in-row and between-row total weed cover to treatment: (1) differences among years in timing photographic measurements and (2) differences among years in corn stand. Photographs of weed cover were taken later after the last mowing in 2001 than in either 2002 or 2003 (Table 3 and Figure 1). Consequently, mowed weeds had progressively less time for weed cover regrowth from 2001 to 2003. As noted earlier, hoeing the weed-free checks was ended shortly after canopy closure to minimize leaf breakage and trampling damage to corn. Consequently, weed-free checks had more total weed cover in 2001 than in other years, although the observed percentage cover did not reduce corn yields in other experiments (Donald 2005).

In 2002, established corn stands were lower than planned (i.e., half of the stand densities for the other two years) (Figures 3 to 5). Consequently, the corn canopy closed later and shaded weeds less completely in 2002 than in either 2001 or 2003. Following between-row mowing in 2002, weeds were exposed to more sunlight, longer, than in other years, and total weed cover recovered better (i.e., it was statistically indistinguishable from the weedy check in 2002). In 2002, preemergence, broadcast-applied atrazine plus S-metolachlor limited between-row total weed cover better than between-row mowing treatments. When corn stands, competition, and shading were reduced in 2002, between-row mowing systems were less able than broadcast-applied herbicides to prevent yield losses.

The contribution of corn stands to corn yields was evident in regression analyses of the combined data across all treatments for each year (Table 5). When stepwise regression was used to model corn yields as a function of crop stands and either between-row or in-row total weed cover and maximum weed canopy height, corn yield models accounted for 45 to 67% of yield variation from 2001 to 2003. In all three years, the stepwise regression procedure selected crop stand and between-row total weed cover terms for inclusion in modeling corn yields. But, the third term chosen for inclusion in regression models varied among years. Corn stands likely influenced between-row total weed cover indirectly via shading. In-row total weed cover was the only term that was never included in models by the stepwise regression procedure.

In two of three years (2001 and 2003), when corn stands were acceptable, between-row mowing systems reduced between-row total weed cover enough to prevent yield loss as well as or better than preemergence broadcast herbicides

Table 5. Regression models for corn yield (kg/ha) selected using stepwise regression in 2001 to 2003.

Year	Model variables	Coefficient B	Standard error of coefficient B	*t*	Significance	Adjusted r^2
2001	Constant	515.081	1,300.247	0.396	0.694	0.45
	In-row maximum weed canopy height (cm)	−42.793	8.168	−5.239	0.000	
	Crop stand (no/ha)	0.007	0.022	3.541	0.001	
	Between-row total weed cover (%)	29.398	12.309	2.388	0.021	
2002	Constant	9,099.766	1,327.451	6.855	0.000	0.67
	In-row total weed cover (%)	−51.236	23.923	−2.142	0.037	
	Crop stand (no/ha)	0.072	0.029	2.456	0.017	
	Between-row total weed cover (%)	−70.143	17.719	−3.959	0.000	
2003	Constant	4,339.257	637.392	6.808	0.000	0.64
	Between-row maximum weed canopy height (cm)	−31.113	6.250	−4.978	0.000	
	Crop stand (no/ha)	0.055	0.012	4.566	0.000	
	Between-row total weed cover (%)	−15.060	5.731	−2.628	0.011	

(SA Mow 1× Middle or Late, SA Mow 2×) (Figures 3 to 5). However, between-row total weed cover was still greater than 40%, and values were much greater than previously observed in no-till (Donald et al. 2001) or reduced-till corn (Donald 2005). Treatments not only reduced between-row total weed cover, but also stunted weeds (Figures 3 to 5).

For both broadcast herbicide treatments (SA Broadcast) and between-row mowing systems (SA Mow 1× Middle or Late, SA Mow 2×), the same preemergence herbicides, atrazine plus S-metolachlor, at the same rates were applied over crop rows. Consequently, it was hypothesized that in-row total weed cover would be ranked as follows: weedy check (SA Weedy) ≫ broadcast herbicide (SA Broadcast) = between-row mowing systems (SA Mow 1× Middle or Late, SA Mow 2×) ≥ weed-free check (SA Weed-free). For unknown reasons, the winter annual weed control treatments influenced this ranking in some years. In two of three years following broadcast herbicide for winter annual weed control (2002 and 2003), values for in-row weed cover of broadcast herbicides were indistinguishable from between-row mowing systems, and greater than the weed-free checks (Figures 3 to 5). In two of three years following between-row mowing for winter annual weed control (2001 and 2002), in-row summer annual weed cover following broadcast herbicide treatment were indistinguishable from between-row mowing systems, but greater than the weed-free checks.

It also was hypothesized that between-row total weed cover would be ranked the same as in-row total weed cover: weedy check (SA Weedy) ≫ broadcast herbicide (SA Broadcast) = between-row mowing systems (SA Mow 1× Middle or Late, SA Mow 2×) ≥ weed-free check (SA Weed-free). However, treatment rank order was less consistent for between-row weed cover than for in-row weed cover (Figures 3 to 5). When corn stands were reduced in 2002, between-row total weed covers of the three between-row mowing systems (SA Mow 1× Middle or Late, SA Mow 2×) exceeded the herbicide treatment (SA Broadcast). In turn, values of between-row cover were inversely related to corn yields for these treatments. When corn stands were as planned, between-row total weed covers either decreased as the number of mowings increased (2001) or was uninfluenced by mowing number (2003). When corn stands were reduced (2002), between-row total weed cover equaled the weedy check and was independent of mowing number.

In earlier research (Donald 2000a, 2000b, 2005; Donald et al. 2001) and in these experiments (Figures 3 to 5), most summer annual total weed cover escaping between-row mowing treatments was giant foxtail. Mowing controlled annual broadleaf and grass weeds differently. The first mowing killed most emerged summer annual broadleaf weeds. After mowing, corn canopy closure and later shading likely limited subsequent germination and emergence of broadleaf weeds. Following one mowing, giant foxtail regrew from tiller buds present in the crown close to the soil surface, below the mowing height. Giant foxtail cover became greater, faster, when corn shading was reduced by decreased or delayed crop canopy closure due to reduced stands. In previous research in reduced- and no-till (Donald 2000a, 2000b; Donald et al. 2001), a second between-row mowing killed the growth of giant foxtail surviving the first mowing. Corn shading likely limited subsequent giant foxtail germination, emergence, and recovery from mowing (Santelmann et al. 1963). Much more giant foxtail cover regrew after one or two mowings in this study (Figures 3 to 5) than in previous research (Donald 2000a, 2000b, 2005; Donald et al. 2001).

Based on either no-till corn yield or between-row total weed cover, there was no advantage to mowing weeds more than once (SA Mow 1× Middle or Late, SA Mow 2×) (Figures 3 to 5), as previously observed for reduced-till corn (Donald 2005). When in-row weed emergence was decreased and delayed by banded preemergence herbicides, only a single, properly timed late between-row mowing (Figure 2) was required to prevent yield loss. Apparently, that single between-row mowing could be delayed after planting, and weeds could be relatively large when it was imposed in either no-till (Figures 2 to 5) or reduced-till corn (Donald 2005).

Published research on the timing of giant foxtail competition in corn (Knake and Slife 1965, 1969; Rajcan and Swanton 2001) did not help explain why one between-row mowing could be delayed so long after planting without corn yield loss (Figures 2 and 3). In most published competition research, weeds were allowed to grow from the time of planting either in corn rows or in the entire plot. In addition, weeds were not usually treated with soil-residual preemergence herbicides, that reduced and delayed weed emergence. In contrast, banded preemergence herbicides in between-row mowing systems kept corn rows weed-free until well after between-row weeds were mowed. Summer annual between-row weeds emerged after corn emerged. Only one published report included treatments in which corn rows were kept free of weeds and weeds were allowed to grow between rows from planting until harvest (Donald and Johnson 2003). When in-row weeds were controlled in reduced-till corn, but between-row weeds competed with corn all season, between-row weeds reduced corn yields as much or more than when between-row weeds were controlled, but in-row weeds competed all season. These two treatments reduced corn yields less than when weeds growing both in and between rows competed with corn until harvest. Although it remains to be proven, between-row weeds are likely to initiate competition with corn later than weeds growing adjacent to corn plants in the row. If weeds growing in rows were controlled with banded preemergence herbicides, the window of opportunity for controlling late emerging weeds between rows was extended, without yield loss (Figures 2 and 3), compared with published competition research (Knake and Slife 1965, 1969; Rajcan and Swanton 2001).

In two of three years in Missouri, between-row mowing systems (WA Mow SA Mow 1× Middle, WA Mow SA Mow 1× Late, or WA Mow SA Mow 2×) controlled and reduced both winter annual and summer annual weed cover as well as broadcast-applied herbicides (WA Broadcast SA Broadcast) (Figures 3 to 5). Consequently, in two of three years, yields were statistically indistinguishable from either the weed-free check (WA Broadcast SA Weed-free, WA Mow SA Weed-free) or the herbicide treatment (WA Broadcast SA Broadcast, WA Mow SA Broadcast) with the following weed management systems: WA Mow SA Mow 1× Middle or WA Mow SA Mow 1× Late or WA Mow SA Mow 2×. Winter annual weeds growing between rows were controlled with one mowing, and summer annual weeds were controlled later with either one late mowing or two mowings (Figures 2 to 5). Achieving planned no-till corn stands was critical for the success of between-row mowing systems. Total herbicide use was reduced 50% (i.e., 25 and 25%, respectively) in no-till corn. Other combinations of herbicides can likely successfully substitute for atrazine plus S-metolachlor for controlling weeds and preventing yield loss in other generic between-row mowing systems.

Sources of Materials

[1] No-till grain drill Model 107, Haybuster Manufacturing, Box 1950, Jamestown, ND 58401.

[2] In 2001 and 2003, John Deere 7100 four-row no-till planter was used, whereas in 2002, a John Deere 7100 four-row no-till planter with modified parts was used, John Deere Des Moines Works, Des Moines, IA 50306-1596.

[3] Teejet flat fan spray nozzle tips 6501 SS, Spraying Systems Co., Wheaton, IL 60187.

[4] Teejet even spray nozzle tips 4001 EVS, Spraying Systems Co., Wheaton, IL 60187.

[5] DR Trimmer/mower 5.0 HP 2-cycle, "XL" Pro, Country Home Products, Ferry Rd., Box 89, Charlotte, VT 05445.

[6] Olympus C4040 Zoom digital camera, Olympus America Inc., Two Corporate Center Dr., Melville, NY 11747-3157.

[7] Sigma Scan Pro version 5 software, SPSS Science, SPSS Inc., 233 South Wacker Drive, 11th Floor, Chicago, IL 60606-6307.

[8] SPSS version 12 software, SPSS Inc., 233 South Wacker Drive, 11th Floor, Chicago, IL 60606-6307.

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