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Row Spacing Influences the Critical Timing for Weed Removal in Soybean (*Glycine max*)[1]

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Abstract: Row spacing affects the time of canopy closure, thus influencing the growth and development of both crop and weeds. Field studies were conducted in 1999, 2000, and 2001 at Mead, NE, and 2000 and 2001 at Concord in eastern Nebraska to determine the effects of three row spacings (19, 38, and 76 cm) on the critical time for weed removal (CTWR) in dryland soybean. A three-parameter logistic equation was fit to data relating relative crop yield to increasing duration of weed presence. In general, earliest CTWR occurred in the 76-cm rows, and coincided with the first trifoliate stage of soybean. Latest CTWR occurred in the 19-cm rows and coincided with the third trifoliate. The CTWR in 38-cm rows occurred at the second trifoliate. Practical implications are that planting soybean in wide rows reduces early-season crop tolerance to weeds requiring earlier weed management programs than in narrower rows.

Nomenclature: Glyphosate-resistant soybean, *Glycine max* (L.) Merr.

Additional index words: Integrated weed management, row spacing, timing of removal, weed interference.

Abbreviations: CPWC, critical period of weed control; CTWR, critical time for weed removal; DAE, days after emergence; DM, dry matter; GDD, growing degree days; HTCs, herbicide tolerant crops; IWM, integrated weed management; POST, postemergence.

INTRODUCTION

One of the first steps in designing optimal weed control systems is to identify the critical period of weed control (CPWC) in major crops (Swanton and Weise 1991). The CPWC is a period in the crop growth cycle during which weeds must be controlled to prevent yield losses (Kasasian and Seeyave 1969; Knezevic et al. 2002; Nieto et al. 1968; Zimdahl 1988). In general, the CPWC has a beginning and an end. Weeds that emerge before or after the CPWC may not represent a threat to crop yields. For example, it was suggested that corn should be kept weed-free from the 3rd to 10th leaf stage (Hall et al. 1992), and soybean from approximately the second trifoliate to the beginning pod (Mulugeta and Boerboom 2000; Van Acker et al. 1993). This information can aid farmers in making decisions on the need for and timing of weed control. However, some suggested that variability inherited with this concept might negate its usefulness (Gunsolus and Buhler 1999; Liebman et al. 2001). Others indicated that the concept is indeed useful to practitioners (Evans 2001; Knezevic et al. 2002; J. Mulliken,[3] personal communication) as a general decision aid for helping achieve an efficient use of postemergence (POST) herbicides. The concept of the CPWC is relatively simple to use, and many producers can easily relate to such an idea (M. Pavlik,[4] personal communication). In addition, producers need a simple tool for timing POST weed control to support their own intuition (S. Keck,[5] personal communication).

The duration of CPWC as well as the crop–weed relationship can vary depending on several factors, including crop and weed characteristics, environmental variables (Hall et al. 1992), and cropping practices such as crop planting density and row spacing (Teasdale 1995). Tollenaar et al. (1994) reported that increasing corn density from 40,000 to 100,000 plants/ha reduced weed biomass by 50%, showing that corn competitiveness with weeds can be enhanced by increasing plant density. Murphy et al. (1996) suggested that narrower rows and higher corn density significantly reduced biomass of late emerging weeds. Similarly, Mulugeta and Boerboom (2000) indicated that soybean planted in 18-cm rows was

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more competitive against weeds than those in 76-cm wide rows. There is interest in evaluating how crop competitiveness changes depending upon the cropping system and, consequently, what is the critical weed free period needed for maximum crop yields. Weed management decisions on the basis of the appropriate timing of herbicide application may result in a significant reduction of production costs, including cropping systems that utilize herbicide-tolerant crops (HTCs).

HTCs represent relatively new weed control technology. Examples of HTCs include soybean, corn (*Zea mays* L.), and canola (*Brassica napus* L.) tolerant to glyphosate and glufosinate (Moll 1997; Rasche and Gadsby 1997). Growers have readily integrated HTCs into their crop production practices. For example, currently more than 60% of 25 million ha of soybean grown in the United States annually are glyphosate-tolerant cultivars (USDA/NASS 2000). In some regions as much as 90% of soybean are glyphosate-tolerant varieties. Even though the use of HTCs may have advantages over conventional herbicide programs, there are risks associated with their use. Herbicide drift, misapplication, weed resistance, weed shifts, and the need for timely application are some of the concerns that must be considered when implementing this relatively new technology (Sikkema et al. 1999). The introduction of HTCs into the North American market enhanced the availability of weed control options and greatly expanded the demand for these herbicides. Glyphosate or glufosinate can also be used as an alternative tool against weeds, thus playing an important role in the development of integrated weed management systems (IWM) (Hamill et al. 1998). The cropping systems utilizing HTCs need to include the fundamental components of IWM such as the knowledge of the CPWC (Hall et al. 1992; Knezevic et al. 2002; Van Acker et al. 1993) and the role of weed thresholds (Bosnic and Swanton 1997; Knezevic et al. 1994, 1995, 1997). These components can also lead to reduced reliance upon the residual type herbicides and provide a well-timed use of low- or nonresidual POST herbicides.

Soybean in Nebraska are grown with row spacings ranging from 19 to 97 cm with 19- and 76-cm row spacing the most common. The general belief is that reducing row spacing affects the competitiveness of both crops and weeds. For example, soybean grown in narrow rows may be more competitive against most weeds because of the fact that narrow row crops close canopy earlier than wide rows and therefore influence light penetration to the soil surface, modifying weed emergence patterns and growth (Knezevic et al. 1999). This raises the question whether reducing soybean row spacing affects weed competitiveness and consequently influences the critical time for weed removal (CTWR). CTWR is a period in the crop growth cycle when weed control must be initiated to protect potential yield. In reality, the CTWR is the beginning stage of the CPWC. Determining effects of row spacing on the CTWR will aid in optimizing weed control strategies. Recognizing this potential interaction will improve acceptance of integrated weed management practices. Therefore there is a need to evaluate the effects of row spacing on the CTWR in soybean. The objective of this study was to determine the effects of three row spacings on the CTWR in dryland soybean.

MATERIALS AND METHODS

Site Description. Field experiments were conducted in 2000 and 2001 at the Haskell Agricultural Laboratory near Concord, NE; and in 1999, 2000, and 2001 at the University of Nebraska Agricultural Research and Development Center near Mead, NE. Soil types were Sharpsburg silty clay loam (fine montmorillonitic, mesic Typic Argiudolls) at Mead; and Kennebec series silty clay loam (fine-silty mixed, mesic Cumulic Hapludolls) at Concord.

Monthly rainfall varied in total amount and periodicity among years and between locations (Table 1). In particular, total rainfall was less than the 30-yr average for Mead in 2001 and both locations in 2000, but significantly greater than the 30-yr average at the Mead site in 1999 and Concord in 2001. Average daily temperatures for the 3-yr study were similar to the 30-yr averages (Table 1).

Experimental Design. The experiment was laid out as a split-plot design with row spacing as the main plot and weed removal as the subplots with four replications of each treatment. The three row spacings included 19, 38, and 76 cm planted at the density of 420,000 seed/ha for each row spacing, resulting in an average plant population of 408,000 soybean plants/ha. Glyphosate-tolerant soybean was planted on June 14 in 1999, and on May 15 and 17 in 2000 at Concord and Mead, respectively. In 2001, planting was done on May 26 at both locations.

A naturally occurring population of mixed weed species was utilized to obtain appropriate duration of weedy periods. Dominant species at Mead were velvetleaf (*Abutilon theophrasti* Medicus), pigweed species (*Amaranthus* spp.), and foxtails (*Setaria* spp.), whereas at Concord pigweeds and foxtails were the most prevalent species. Combined densities of all weed species ranged

Table 1. Monthly rainfall (mm) and the mean daily temperature (C) for Concord and Mead during the 1999, 2000, and 2001 growing seasons and the long-term (30-yr) averages.

		Rainfall				Temperature			
Location	Month	1999	2000	2001	30-yr average	1999	2000	2001	30-yr average
		mm				C			
Concord									
	April	—	34	112	63	—	10	10	10
	May	—	139	116	98	—	17	17	16
	June	—	158	51	106	—	20	21	22
	July	—	45	119	79	—	23	24	24
	August	—	41	112	74	—	23	22	22
	September	—	16	69	67	—	18	16	17
	Total	—	433	579	487				
Mead									
	April	141	51	55	69	10	11	12	11
	May	149	70	225	109	16	19	17	19
	June	128	152	46	107	20	21	21	22
	July	55	88	22	83	26	24	25	25
	August	80	55	64	86	22	25	24	23
	September	70	22	74	88	17	20	18	18
	Total	623	438	485	542				

from 65 to 96 shoots/m² at Mead, and 115 to 142 shoots/m² at Concord. Most weeds emerged within a few days of crop emergence (±2d). Weed removal was achieved with application of commercially formulated glyphosate at the labeled rate of 1,140 g ai/ha with ammonium sulfate (3.2 kg/ha) as an adjuvant. Applications were made with a bicycle-wheel sprayer calibrated to deliver a solution volume of 187 L/ha.

The timing of weed removal was according to the soybean development stage. Average soybean development stage was determined by examining 10 consecutive plants selected arbitrarily in each plot. Soybean development stage was on the basis of the number of fully developed nodes per plant; a fully developed leaf node was one that had a leaf above it with expanded leaflets.

Table 2. Parameter estimates (standard error) by site–year for a linear regression (y = a + b × x) relating row spacing (x-axis) to soybean yield in season-long weedy and weed-free plots (Figure 1).

			Parameter estimates[a]		
Location	Year	Weediness level	a	b	R^2
Mead					
	1999	Weedy	2,819 (327) a	− 18 (6) a*[b]	0.88
		Weed-free	3,340 (508) a	− 4 (1) b*	0.34
	2000	Weedy	2,540 (470) a	− 26 (9) a*	0.88
		Weed-free	3,200 (479) a	− 6 (3) b*	0.62
	2001	Weedy	1,530 (651) a	− 5 (1) a*	0.31
		Weed-free	3,120 (90) b	− 3 (1) a	0.75
Concord					
	2000	Weedy	1,480 (81) a	− 10 (2) a*	0.97
		Weed-free	2,630 (49) b	− 2 (0.1) b	0.99
	2001	Weedy	640 (490) a	5 (3) a*	0.33
		Weed-free	2,740 (306) b	2 (0.6) a	0.33

[a] Within a column, location, and year, the same letter indicates that the parameter values did not differ significantly according to a *t* test (P = 0.05).

[b] * Slopes (b) significantly different from zero based on a *t* test at P = 0.05.

The use of soybean-leaf stage allowed determination of the critical period on the basis of the phenological development of the crop. Weeds were allowed to grow until: first trifoliate stage (V1), second trifoliate stage (V2), third trifoliate stage (V3), beginning pod (R3), and beginning seed (R5) and then removed. In addition, there were season-long weedy and weed-free controls. Each plot was 4.6 m wide and 10 m long. Observations were not taken from the first 2 m at the front and back of each plot. Each plot had six crop rows in 76-cm row spacing, 12 rows in 38-cm rows, and 22 rows in 19-cm wide rows. Four replications were separated by 1.5-m alleyways. Two buffer rows were planted on either end of the main split plot and four buffer rows on either side of the trial. Each experiment was established in the middle of a larger production field.

To characterize the early-season competitive environment at each site, mean weed density for each species was measured in all plots at the V3 stage (Table 2). In addition, weed density and species composition was also assessed in all plots before every weed removal activity (not shown). Weed counts were conducted from two 0.25-m² quadrats placed within 2 m from the top and bottom edges of the plot in 2001. Because of labor constraints in 1999 and 2000, weed density was assessed in each plot using a visual descriptive scale (e.g., low, medium, high). Weed density, including all species, in 1999 and 2000 ranged from 20 (low) to 200 (high) plants/m².

Final crop harvest was conducted approximately 1 to 2 wk after physiological maturity. In 1999, final harvest was October 11, whereas in 2000 it was October 11 and 16 for Concord and Mead, respectively. Soybean in 2001 was harvested on October 1 and 18 at Concord and Mead, respectively. Yields from each subplot were machine harvested from the middle rows (2, 4, and 8 rows for 76, 38, and 19 cm, respectively) for a full length of the plot. Seeds were dried at 70 C to a constant weight. All yields are presented and analyzed on a dry weight basis.

Data Analysis. Actual yields and relative yields were subjected to an overall ANOVA using PROC MIXED (Littell et al. 1996) in SAS (SAS 1999). Relative yield of each experimental unit was calculated as a percent of the corresponding weed-free yield for each row spacing. The significance of interactions between years, locations, and treatment combinations were evaluated at the $P = 0.05$ level, following the procedure outlined by Knezevic et al. (2002).

A three-parameter logistic equation, modified slightly from the form proposed by Hall et al. (1992), was used to describe the effect of increasing duration of weed interference on relative yield and to determine the CTWR for each row spacing within each site–year:

$$\mathrm{RY} = \left\{\left[\frac{1}{\exp[K^*(\mathrm{GDD} - D)] + F}\right] + \left(\frac{F - 1}{F}\right)\right\} \times 100 \qquad [1]$$

where RY is relative yield (percentage of season-long weed-free yield), GDD is the duration of weed interference measured from the time of planting in growing degree days (C d), D is the point of inflection in growing degree days, and K and F are constants.

Air growing degree days (GDDs) were used as the explanatory variable and calculated using the method described by Gilmore and Rogers (1958). The time of crop planting was used as the reference point for accumulation of GDD to account for the possibility of weeds emerging before the crop. The GDD corresponding to the CTWR was then related to crop growth stage so that the CTWR could be expressed in terms of crop phenological development. The regression was conducted using GDD as a quantitative variable because it is (1) a biologically meaningful measure of time required for plant growth and development (Gilmore and Rogers 1958), (2) more easily used into regression models than a categorical variable such as crop growth stage because it provides a continuous and precise scale for the x-axis (for example, x-axis solely on the basis of the crop growth stage is a continuous scale only during vegetative growth [e.g., leaf stages 1 to 15]); however, the scale becomes ‘‘uncertain’’ while attempting to define data points during reproductive growth (e.g., beginning or midgrain-fill period), and (3) can be used as a more appropriate means of comparing data from different locations, years, and planting dates. GDD can be also related to the crop growth stage, which can be quickly assessed in the field, and then conveyed more easily to producers, consultants, and other field personnel (Knezevic et al. 2002; Martin et al. 2001). The use of GDD also allows for the comparison of CTWR among years, which allows for the investigation of non–crop-related reasons for the timing of the CTWR.

Determination of the CTWR in this study was on the basis of an acceptable yield loss level of 5%. A 5% acceptable yield loss level was selected assuming (1) acceptance with producers, (2) reliable detection of treatment effects despite natural variability in yield, and (3) statistical significance at the 95% level. The GDD estimate corresponding to 95% relative yield was calculated from equation 1 described above for each year–site combination and then related to the corresponding crop-growth stage.

A linear regression ($y = a + b \times X$) was used to describe the relationship between row spacing and soybean yield in season-long weedy and weed-free plots. Slopes (b) were tested (t test at 5% significance) for difference from zero to determine significant effects of row spacing on soybean yield.

Parameter estimates for both logistic and linear regressions were determined using FIG-P.[6] Significant differences between the regression lines describing each row spacing within a data set were determined by comparing parameter estimates and respective standard errors (±SE) using t and F tests at the 5% significance level. If all regression coefficients of compared models were not significantly different on the basis of SE, the data could have been combined among row spacings, locations, and years. Parameter estimates are considered reliable if the standard error is less than half of the numerical value of the estimate (Koutsoyiannis 1973).

RESULTS AND DISCUSSION

Soybean Yield Response to Row Spacing. Soybean yields varied among locations and years (Figure 1). Yields from season-long weed-free plots ranged from 2,650 to 3,520 kg/ha, compared with much lower yields of 440 to 2,330 kg/ha in season-long weedy plots. Location-related differences in weed-free yield were likely

[6] The Scientific Figure Processor, 1992. FIG-P Software Corporation, Durham, NC.

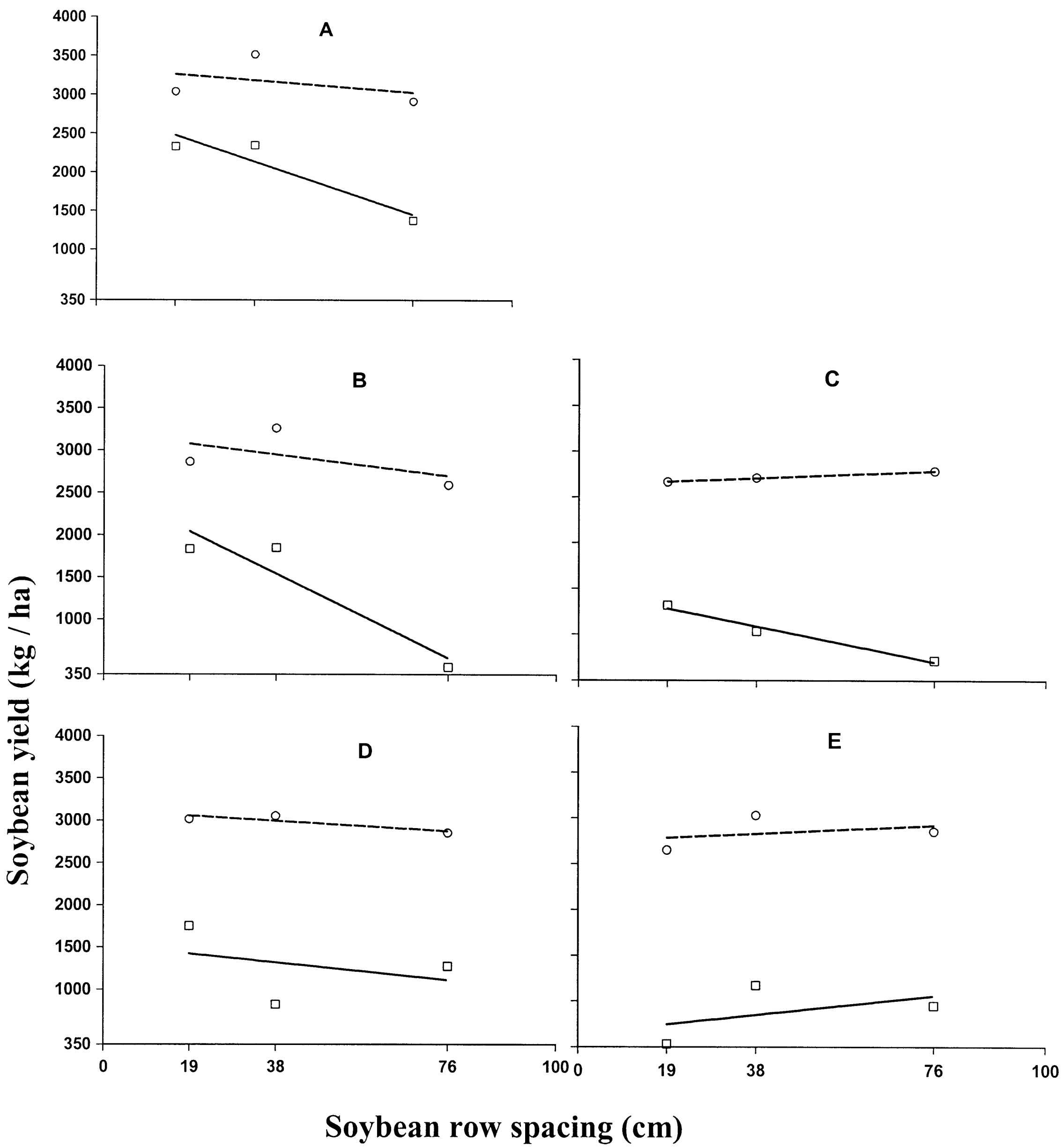

Figure 1. Mean soybean yield response to three row spacing in the season-long weedy (□) and season-long weed-free (○) plots at (A) Mead in 1999, (B) Mead in 2000, (C) Concord in 2000, (D) Mead in 2001, and (E) Concord in 2001. Parameter values for regression lines (Y = a + b × X) and significance of the slopes (b) are presented in Table 2.

because of rainfall amount and periodicity. For example, total rainfall for the growing season was the greatest in 1999 at Mead (Table 1), resulting in higher weed-free yields than for any other site (Figure 1).

There was no consistent response of soybean yields to row spacing in season-long weed-free plots (Figure 1). The significant yield response to row spacing, on the basis of significant slopes (Table 2), was observed at Mead in 1999 and 2000. However, the slopes were not significant for three data sets (i.e., Concord in 2000, 2001, and Mead in 2001). It is likely the effect of a straight line fitted through only three data points (i.e., three row spacings). In each of the three data sets crop yields were lower in 19- and 76-cm rows than in 38-cm rows, which has flattened the regression line. This absence of a response to row spacing in weed-free conditions is somewhat contrary to previous reports by Elmore (1998), who suggested that soybean planted in 25-cm rows yielded about 10% higher than soybean planted in 76-cm wide rows.

However, there was a significant response of soybean yields to row spacing in season-long weedy plots in four

Table 3. Parameter estimates (standard error) by site–year and row spacing (cm) for the three-parameter logistic model characterizing the influence of the duration of weed interference on the relative yield of soybean (Figure 2).

Location	Year	Row spacing	Parameter estimates[a]			
			K	*D*	*F*	R^2
Mead						
	1999	19	0.0043 (0.0009) a	328 (73) a	3.9 (0.4) a	0.98
		38	0.0073 (0.0006) b	242 (1) b	3.2 (0.6) a	0.96
		76	0.003 (0.002) c	245 (35) ab	1.9 (0.3) b	0.74
	2000	19	0.003 (0.001) a	614 (118) a	2.5 (0.4) a	0.95
		38	0.007 (0.001) b	381 (15) b	2.2 (0.1) a	0.98
		76	0.009 (0.001) c	447 (20) c	1.2 (0.02) b	0.99
	2001	19	0.012 (0.001) a	474 (15) a	2.4 (0.05) a	0.99
		38	0.003 (0.001) b	847 (240) b	1.2 (0.02) b	0.96
		76	0.002 (0.009) b	1,174 (570) b	1.1 (0.6) b	0.95
Concord						
	2000	19	0.006 (0.0002) a	537 (11) a	1.9 (0.02) a	0.99
		38	0.005 (0.003) b	579 (24) b	1.6 (0.04) a	0.99
		76	0.004 (0.0004) c	601 (27) b	1.3 (0.07) b	0.99
	2001	19	0.007 (0.0006) a	634 (16) a	1.2 (0.03) a	0.99
		38	0.006 (0.0003) a	504 (18) b	1.6 (0.03) b	0.99
		76	0.005 (0.0004) b	574 (31) c	1.2 (0.04) ab	0.99

[a] Within a column, location, and year, the same letter indicates that the parameter values did not differ significantly according to a *t* test (P = 0.05).

out of five data sets (Figure 1). An increase in crop row spacing resulted in lower yields at all locations but one. At Concord in 2001, soybean yields were lowest in 19-cm rows, possibly because of higher weed density than in 38- and 76-cm-wide rows (data not shown). A general trend of highest yields in 19-cm rows under season-long weedy conditions may indicate better crop competitiveness against weeds than in wider rows.

Critical Time for Weed Removal. Because significant two-way interactions between locations within years and treatment levels were observed (data not shown), all yield data were further analyzed separately for each site–year. Even though the regression lines appear similar at some sites (e.g., at Concord, 2000), the lines are significantly different from each other on the basis of the regression coefficients (Table 3).

Table 4. Estimates of the critical time for weed removal on the basis of growing degree days (GDD), crop growth stage (CGS) and days after emergence (DAE) by site–year and row spacing calculated using three-parameter logistic equation.

Location	Year	Row spacing	Critical time for weed removal		
			GDD	CGS	DAE
Mead					
	1999	19	310	V3	19
		38	170	V2	12
		76	110	V1	6
	2000	19	350	V3	21
		38	190	V2	13
		76	130	V1	7
	2001	19	360	V4	24
		38	130	V2	11
		76	100	V1	6
Concord					
	2000	19	360	V4	25
		38	180	V2	13
		76	110	V1	6
	2001	19	270	V3	21
		38	190	V2	13
		76	100	V1	6

Despite an inconsistent yield response to row spacing (Figure 1), the CTWR was consistent and delayed substantially by reduced row spacing at all locations (Table 4; Figure 2). The CTWR ranged from 100 to 130 GDD corresponding to the V1 stage of soybean development in 76-cm row spacing. In 38-cm rows, the CTWC ranged from 160 to 190 GDD, which corresponded approximately to the V2 stage of soybean development. The CTWR for the 19-cm rows ranged from 270 to 360 GDD, corresponding to the growth stages ranging from V3 to V4 stages.

These results indicate that increasing row spacing from 19 to 76 cm reduces soybean early-season tolerance to weeds. The mechanisms by which the wider rows reduced soybean tolerance to weed interference are not completely understood. Perhaps the wider row spacing provides additional space and advantage to weeds for early-season growth relative to the weeds in narrow rows. Consequently, weeds may be better competitors earlier in wide than in narrow rows, resulting in an early CTWR. It is likely because of competitive advantage for the weeds in terms of preemption of soil and light resources. Similarly, the mechanism of soybean tolerance to weed presence in 19-cm rows has yet to be described. We suggest that it may be related to the change in the quality and quantity of light because of crop shading effects. We also observed that

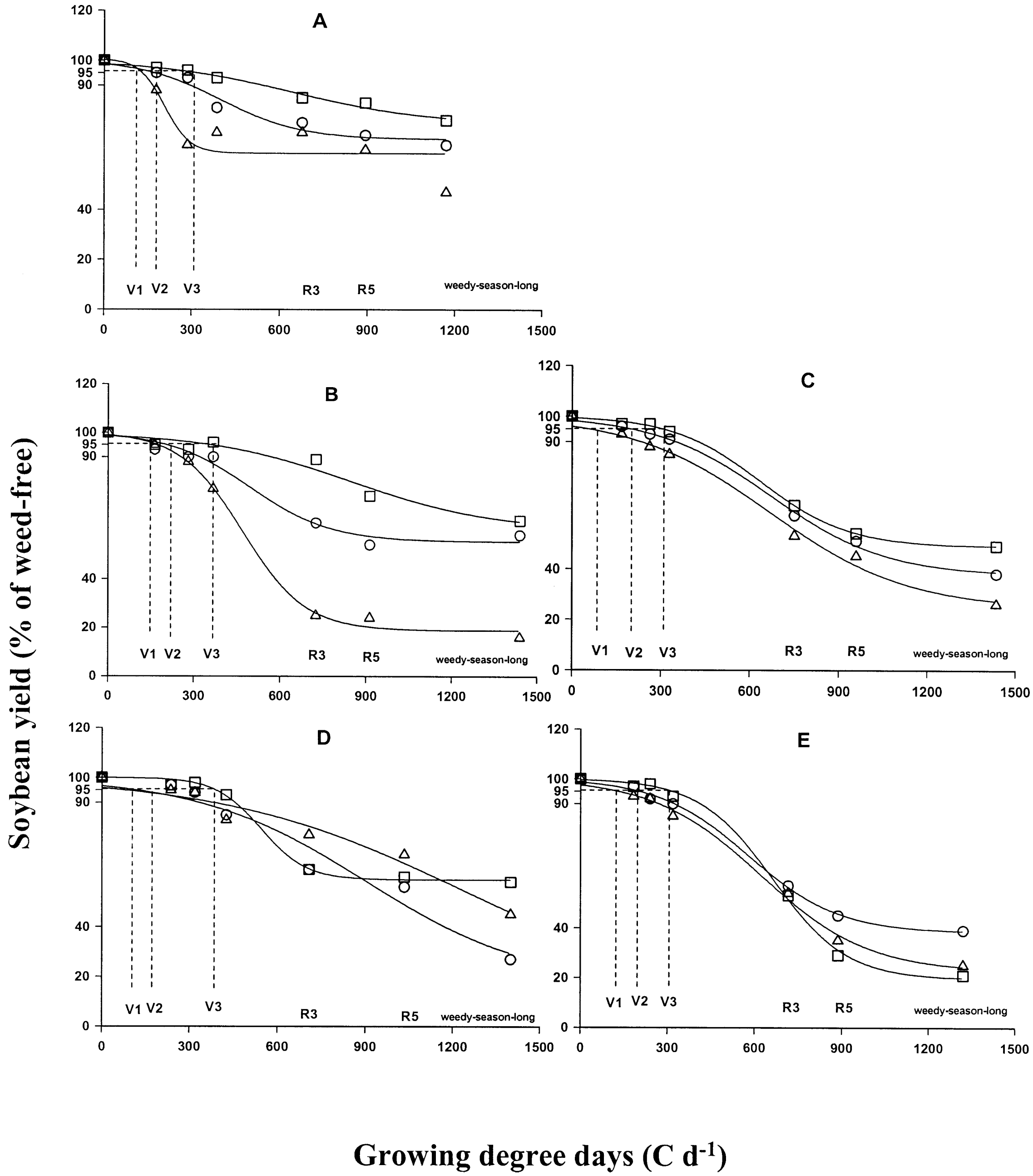

Figure 2. Soybean relative yield response to increasing duration of weed interference in 19-cm (□)–, 38-cm (○)–, and 76-cm (Δ)–wide rows at (A) Mead in 1999, (B) Mead in 2000, (C) Concord in 2000, (D) Mead in 2001, and (E) Concord in 2001. Horizontal dashed lines indicate the 5% acceptable yield loss level used to determine the critical time for weed removal, whereas vertical dashed lines indicate the growing degree days and crop grow stage which produce a model solution equivalent to 95% relative yield (i.e., V1, V2,V3). Parameter values for logistic model are presented in Table 3.

even though weeds were present in the narrow row plots at similar densities as in other row spacings, they did not grow as vigorously and thus were not as competitive against the crop in 19-cm rows compared with 38- and 76-cm wide rows. This area needs further investigation.

Implications for Integrated Weed Management. This study confirmed that the crop row spacing significantly influenced crop–weed interference relationships. These results support previous findings (Burnside 1979; Mulugeta and Boerboom 2000) that weeds may be allowed to compete with soybean for longer periods when crop is planted in narrow rows than in wide rows, at least for the species combinations and environmental conditions under which these experiments were conducted. The differences in the CTWR documented in this study highlight the importance of integrating decisions regarding crop row spacing and the timing of weed control.

The practical implication of this study is that planting soybean in wide rows (i.e., 76 cm) reduces early-season crop tolerance to weeds, thus requiring earlier weed management practices than in narrower rows. In contrast, a reduction in soybean row spacing increases soybean tolerance to weeds and may require less intensive weed management programs.

With the growing popularity of HTCs, dependence upon total POST programs likely will become more prevalent in future cropping systems. Such a shift in cropping practices highlights the importance for appropriately timed weed control measures. Because glyphosate-tolerant soybean have been widely adopted, the concept of CTWR is an important part of IWM in answering some fundamental questions such as ''if'' and ''when'' to apply POST herbicides. A generally sound strategy for weed control in, for example, glyphosate-tolerant soybean, would be to apply glyphosate tank-mixed with a short residual herbicide at the CTWR, which may provide adequate weed control for the entire critical period (Knezevic et al. 2002).

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