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Research Article

Critical time for weed removal in glyphosate-resistant soybean as influenced by preemergence herbicides

Stevan Z. Knezevic[1], Pavle Pavlovic[2], O. Adewale Osipitan[3], Ethann R. Barnes[4], Clint Beiermann[4], Maxwel C. Oliveira[5], Nevin Lawrence[6], Jon E. Scott[7] and Amit Jhala[8]

[1]Professor, Northeast Research and Extension Center, University of Nebraska–Lincoln, Lincoln, NE, USA; [2]Visiting Student, Northeast Research and Extension Center, University of Nebraska–Lincoln, Lincoln, NE, USA; [3]Postdoctoral Research Associate, Northeast Research and Extension Center, University of Nebraska–Lincoln, Lincoln, NE, USA; [4]Graduate Student, Department of Agronomy and Horticulture, University of Nebraska–Lincoln, Lincoln, NE, USA; [5]Former Graduate Student, Department of Agronomy and Horticulture, University of Nebraska–Lincoln, Lincoln, NE, USA; [6]Assistant Professor, Panhandle Research and Extension Center, University of Nebraska–Lincoln, Lincoln, NE, USA; [7]Research Technologist, Northeast Research and Extension Center, University of Nebraska–Lincoln, Lincoln, NE, USA; [8]Associate Professor, Department of Agronomy and Horticulture, University of Nebraska–Lincoln, Lincoln, NE, USA

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Author for correspondence:
Stevan Z. Knezevic, Northeast Research and Extension Center, University of Nebraska–Lincoln, Lincoln, NE 68588.
Email: sknezevic2@unl.edu

Abstract

Widespread and repeated use of glyphosate resulted in an increase in glyphosate-resistant (GR) weeds. This led to an urgent need for diversification of weed control programs and use of PRE herbicides with alternative sites of action. Field experiments were conducted over a 4-yr period (2015 to 2018) across three locations in Nebraska to evaluate the effects of PRE-applied herbicides on critical time for weed removal (CTWR) in GR soybean. The studies were laid out in a split-plot arrangement with herbicide regime as the main plot and weed removal timing as the subplot. The herbicide regimes used were either no PRE or premix of either sulfentrazone plus imazethapyr (350 + 70 g ai ha^{-1}) or saflufenacil plus imazethapyr plus pyroxasulfone (26 + 70 + 120 g ai ha^{-1}). The weed removal timings were at V1, V3, V6, R2, and R5 soybean stages, with weed-free and weedy season-long checks. Weeds were removed by application of glyphosate (1,400 g ae ha^{-1}) or by hoeing. The results across all years and locations suggested that the use of PRE herbicides delayed CTWR in soybean. In particular, the CTWR without PRE herbicides was determined to be around the V1 to V2 (14 to 21 d after emergence [DAE]) growth stage, depending on the location and weed pressure. The use of PRE-applied herbicides delayed CTWR from about the V4 (28 DAE) stage up to the R5 (66 DAE) stage. These results suggest that the use of PRE herbicides in GR soybean could delay the need for POST application of glyphosate by 2 to 5 wk, thereby reducing the need for multiple applications of glyphosate during the growing season. Additionally, the use of PRE herbicides could provide additional modes of action needed to manage GR weeds in GR soybean.

Introduction

With the commercialization and adoption of glyphosate-resistant (GR) soybean as well as GR corn (*Zea mays* L.), GR canola (*Brassica napus* L.), GR alfalfa (*Medicago sativa* L.), and GR sugar beet (*Beta vulgaris* L.), the use of glyphosate for weed control has increased drastically over the last 20 yr (Heap and Duke 2018), especially in the United States. This widespread and repeated use of glyphosate resulted in the development of glyphosate resistance in 38 species worldwide, of which 17 were found in the United States. This alarming trend requires an urgent need for integrated and diverse approaches to weed management (Beckie and Harker 2017; Buhler et al. 2000; Owen 2016), which should aid in reducing multiple applications of glyphosate. One such approach should be based on the concept of critical period of weed control.

Critical period of weed control (CPWC) could be a very important component of integrated weed management, as it has potential to provide guidelines for the use of PRE herbicides and the timing for POST herbicide application (Knezevic et al. 2003). In essence, the CPWC represents the time interval between two separately measured crop–weed competition components: the critical time for weed removal (CTWR) and the critical weed-free period. During crop emergence, resources present in the environment may be sufficient to support both weed and crop growth. However, with continued competition between weeds and crops, the weeds are no longer tolerated due to negative effects on the crop, marking the beginning of the CPWC, which is also referred to as the CTWR (Knezevic et al. 2002). The CTWR can be influenced by several factors, including crop and weed characteristics (Tursun et al. 2016), environmental variables

(Knezevic 2007; Tursun et al. 2016), cropping practices such as crop planting density and row spacing (Adigun et al. 2014; Osipitan et al. 2016; Teasdale 1995), soil nutrients (Evans et al. 2003; Knezevic et al. 2002; Odero and Wright 2013), and PRE weed control program (Knezevic et al. 2013).

Understanding how PRE herbicides could influence the CTWR will aid in optimizing weed control strategies and allow for the development of better resistance-management strategies (Knezevic et al. 2013). Hence, the objective of this study was to determine how PRE herbicides would influence CTWR in GR soybean across years and locations in Nebraska.

Table 1. Soil texture and composition in 2015, 2016, and 2017 at Concord (HAL); 2017 and 2018 at Clay Center (SCAL); and 2018 at Scottsbluff (PAN), NE[a].

Site	Year	Soil texture	Sand	Silt	Clay	OM	pH	CEC
			——	——%	——	——		mEq/100 g
HAL	2015	Silty loam	24	56	20	3.1	5.6	14.3
	2016	Silty clay loam	16	52	26	3.5	6.4	23.8
	2017	Silty clay loam	20	54	32	4.7	6.1	30.8
SCAL	2017	Silty clay loam	17	58	25	3.1	6.5	17.2
	2018	Silty clay loam	16	57	27	2.8	6.4	16.9
PAN	2018	Sandy loam	78	8	13	1.3	6.1	17.8

[a]Abbreviations: CEC, cation exchange capacity; OM, organic matter

Table 2. Total monthly precipitation and average temperature from May to October in 2015, 2016, and 2017 at Concord (HAL); 2017 and 2018 at Clay Center (SCAL); and 2018 at Scottsbluff (PAN), NE.

	Precipitation					
	HAL			SCAL		PAN
Month	2015	2016	2017	2017	2018	2018
			——mm——			
May	72	94	94	154	128	63
June	130	84	14	23	107	72
July	143	8	39	51	99	46
August	83	131	246	90	88	33
September	178	66	49	24	62	30
October	0	40	88	0	52	29
			——Temperature (C)——			
May	14.7	15	14.4	15.7	15.8	14.1
June	21.4	23	22.2	22.7	21.7	19.6
July	22.5	22.7	24.2	24.8	24.2	23.1
August	20.5	21.6	19.4	20.7	23.1	22.2
September	19.7	18.6	18	19.5	18.2	16.5
October	15	11.6	12.7	14.9	11.3	9.2

Materials and methods

Experimental site description

Field trials were conducted over a period of 4 yr at three Nebraska locations: Haskell Agricultural Laboratory (HAL), Concord (42.37°N, 96.95°W), in 2015, 2016, and 2017; South Central Agricultural Laboratory (SCAL), Clay Center (40.52°N, 98.05°W), in 2017 and 2018; and Panhandle Research and Extension Center (PAN), Scottsbluff (41.87°N, 103.67°W), in 2018. The soil texture for all locations was silty clay loam irrespective of the year of study, except at HAL in 2015 (silty loam) and PAN (sandy loam) (Table 1). The soil pH was slightly acidic (5.6 to 6.4) for all years or locations (Table 1). The organic matter content and cation exchange capacity (CEC) of soils ranged from 1.3% to 4.7% and 14.3 to 30.8 mEq/100 g, respectively (Table 1).

The GR soybean was planted in 76-cm row spacing. At HAL, the seeding rates were 369,000, 371,000, and 370,000 seeds ha^{-1} planted on May 31, June 9, and May 15 in 2015, 2016, and 2017, respectively. Seeding rate at SCAL was 346,000 seeds ha^{-1}, planted on April 24 and 25 in 2017 and 2018, respectively. Seeding rate at PAN (May 12, 2018) was 349,000 seeds ha^{-1}. At all locations, planting was done mechanically; for example, a John Deere® Finger Pickup Planter (1819 Chiefs Way, Wayne, NE 68787) was used at HAL, and a Monosem NG Plus Planter (1001 Blake Street, AQ907 Edwardsville, KS 66111) was used at PAN. Plot sizes were 8 m by 3 m at the HAL location, and 9 m by 2 m at the SCAL and PAN locations. Soybean varieties were ‘Pioneer® 92Y70’ (2015; DuPont Pioneer, Johnston, IA 50131), ‘NK S27-J7’ (2016; Syngenta, Greensboro, NC 27419), and ‘NK SJ-27’ (2017) at HAL; ‘NK S27-J7’ (2017 and 2018) at SCAL; and ‘AG20X7’ (2018; Monsanto, Lindbergh Boulevard, St Louis, MO 63167) at PAN. Before planting, fields were conventionally tilled and disked. Average monthly air temperatures and total rainfall varied among years and between locations (Table 2).

Experimental design

Trials were established as a randomized complete block design in a split-plot arrangement. The presence of PRE herbicide (PRE) or absence (no PRE) represented the main plots. PRE herbicide was either sulfentrazone plus imazethapyr (350 + 70 g ai ha^{-1}; Authority Assist®, FMC, 2929 Walnut Street, Philadelphia, PA 19104) or saflufenacil plus imazethapyr plus pyroxasulfone (26 + 70 + 120 g ai ha^{-1}; Zidua® PRO, BASF, 26 Davis Drive, Research Triangle Park, NC 27709). In 2015, only sulfentrazone plus imazethapyr was used as a PRE herbicide. In 2016 and 2017, at the HAL location, sulfentrazone plus imazethapyr and saflufenacil plus imazethapyr plus pyroxasulfone were used separately as PRE herbicides. At the SCAL location, in 2017 and 2018, and at Scottsbluff in 2018, saflufenacil plus imazethapyr plus pyroxasulfone was used as the PRE herbicide. The subplot treatments consisted of seven weed removal timings (weeds were allowed to grow until predetermined growth stage of soybean): first trifoliate (V1), third trifoliate (V3), sixth trifoliate (V6), full flowering (R2), early seed (R5) of soybean, with weed-free and weedy season-long checks. There were four soybean rows in each subplot. Treatments were replicated eight times in 2015 and four times in 2016, 2017, and 2018 at all locations. Weeds were removed at each timing by the application of glyphosate (1,400 g ae ha^{-1}, Roundup PowerMax®, Monsanto), except at R2 and R5 soybean growth stages, when weed removal was done by hoeing. After the specified removal times, plots were kept weed-free for the rest of the season either by application of glyphosate or by hoeing.

Herbicide applications were conducted with a CO_2-pressurized backpack sprayer with TeeJet® flat-fan nozzles (Spraying Systems, Wheaton, IL 60187) spaced at 56 cm and calibrated to deliver 140 L ha^{-1} of aqueous solution. PRE herbicides were applied with TeeJet® AIXR 110020 (2015, 2016, and 2017 at HAL) or TeeJet® AIXR 110015 nozzles (2017 and 2018 at SCAL and PAN). POST herbicide applications were conducted with TeeJet® AIXR 110020 (2015) or TeeJet XRC 80020 nozzles (2016, 2017, and 2018).

Data collection and analysis

Temperatures were recorded hourly with data loggers throughout the growing seasons. Temperatures were converted to soybean growing degree days (GDD) after emergence using the method

Table 3. Average weed density and species composition in 2015, 2016, and 2017 at Concord (HAL); 2017 and 2018 at Clay Center (SCAL); and 2018 at Scottsbluff (PAN), NE.

Site	Year	Weed species	Type	Density	Total population
				plants m^{-2}	%
HAL	2015	*Setaria viridis* (L.) P. Beauv.	Grass	87	83
		Amaranthus tuberculatus (Moq.) J. D. Sauer	Broadleaf	13	12
		Abutilon theophrasti Medik.	Broadleaf	2	2
		Amaranthus retroflexus L.	Broadleaf	2	2
		Ipomoea hederacea Jacq.	Broadleaf	1	1
	2016	*Amaranthus tuberculatus* (Moq.) J. D. Sauer	Broadleaf	9	49
		Chenopodium album L.	Broadleaf	9	45
		Abutilon theophrasti Medik.	Broadleaf	1	2
		Amaranthus retroflexus L.	Broadleaf	1	2
		Setaria viridis (L.) P. Beauv.	Grass	1	2
	2017	*Amaranthus tuberculatus* (Moq.) J. D. Sauer	Broadleaf	54	48
		Setaria viridis (L.) P. Beauv.	Grass	30	27
		Abutilon theophrasti Medik.	Broadleaf	15	13
		Chenopodium album L.	Broadleaf	13	12
SCAL	2017	*Setaria viridis* (L.) P. Beauv.	Grass	22	23
		Amaranthus tuberculatus (Moq.) J. D. Sauer	Broadleaf	20	21
		Amaranthus palmeri S. Watson	Broadleaf	17	17
		Abutilon theophrasti Medik.	Broadleaf	12	12
		Chenopodium album L.	Broadleaf	5	6
		Others		20	20
	2018	*Amaranthus palmeri* S. Watson	Broadleaf	43	30
		Abutilon theophrasti Medik.	Broadleaf	36	26
		Setaria viridis (L.) P. Beauv.	Grass	33	24
		Amaranthus retroflexus L.	Broadleaf	28	19
		Chenopodium album L.	Broadleaf	6	1
PAN	2018	*Chenopodium album* L.	Broadleaf	55	65
		Amaranthus palmeri S. Watson	Broadleaf	26	30
		Eragrostis cilianensis (All.) Vignolo ex Janch.	Grass	4	5

described by Gilmore and Rogers (1958). The GDD (equivalent to weed removal timing) was used as the explanatory variable and calculated as follows:

$$\mathrm{GDD} = \sum \left[\frac{T_{\max}+T_{\min}}{2}\right] - T_{\mathrm{base}} \qquad [1]$$

where $T_{\max}$ and $T_{\min}$ are daily maximum and minimum air temperatures (C), respectively, and T_{base} is the base temperature (10 C) for soybean growth.

Species composition and weed density for each weed species were collected in all plots before weed removal. Weed counts were conducted within 0.25-m^2 quadrats placed in the middle of each plot. Yield components (plants m^{-2}, pods per plant, seeds per pod, and 100-seed weight) were collected in 2017 (HAL and SCAL) and 2018 (SCAL and PAN) by clipping soybean plants within a 50-cm length of one of the two middle rows in each plot. Soybean was harvested using an Almaco SP40 combine harvester (1819 Chiefs Way, Wayne, NE 68787) from the entire row length of the two middle rows in each plot in 2015 and 2016 at HAL and in 2018 at PAN. At SCAL (2017 and 2018), a Gleaner K2 combine harvester (AGCO, 4205 River Green Parkway, Duluth, GA 30096) was used to harvest from the entire row length of the two middle rows in each plot. At HAL (2017), 3 m of soybean were hand harvested from two middle rows of each plot and then threshed to determine yield. Yields from all locations were generally reported at 13% moisture.

ANOVA was conducted to test for significance of location and year of study using the PROC GLM procedure in SAS v. 9.4 software (SAS Institute, 100 SAS Campus Drive, Cary, NC 27513). A four-parameter log-logistic regression model described the relationship between soybean yield, yield components or yield loss, and weed removal timings (in GDD) using the following equation (Hall et al. 1992; Knezevic et. al. 2007):

$$Y = \frac{C + (D - C)}{\{1 + \exp[B(\log X - \log E)]\}} \qquad [2]$$

where Y is the response (yield, yield components, or yield loss); C is the lower limit; D is the upper limit; X is the GDD calculated after soybean emergence; E is the GDD at the inflection point (also abbreviated as ED_{50} or I_{50}), and B is the slope of the line around the inflection point.

The GDD (and the corresponding DAE [days after emergence] and SGS [soybean growth stage]) required for a 5% yield loss (ED_5) for no PRE and PRE herbicide treatments were calculated from the regression curves and compared using standard errors (Knezevic et al. 2018). The ED_5, was considered the CTWR. All regression analyses and graphs were performed in R (R Development Core Team 2017) using the dose–response curves ('drc') statistical package (Knezevic et al. 2007).

Results and discussion

Weed density and species composition

Weed density and species composition varied with years and locations (Table 3). There were more dicot species than monocot species at all locations, except at HAL in 2015. For example, at HAL in 2015, there was a higher presence of grassy species (83%) compared with broadleaf species (17%), while there were more

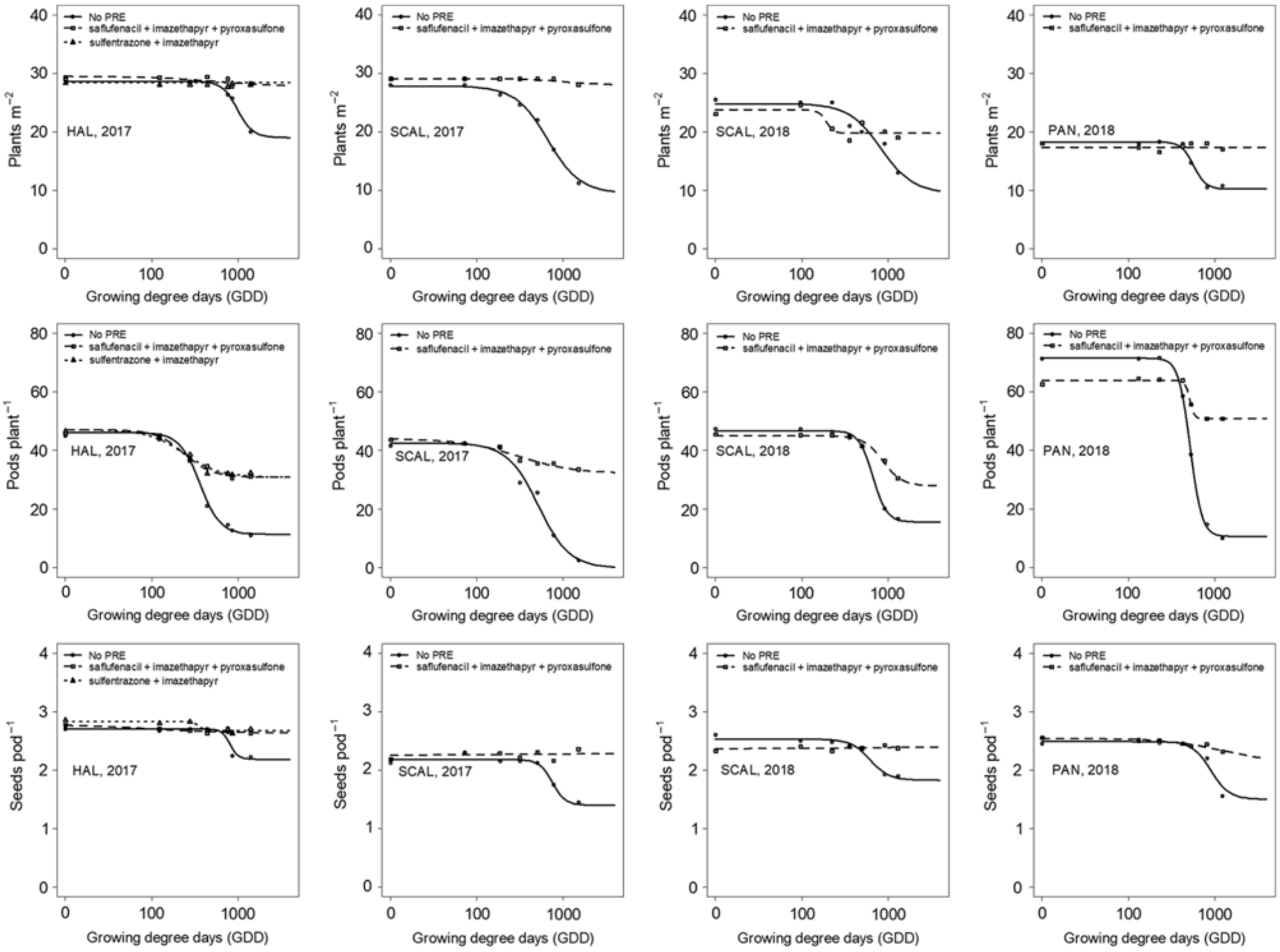

Figure 1. Soybean yield components as a function of increasing delay of weed removal for no PRE and PRE herbicide applications at Concord (HAL in 2017), Clay Center (SCAL in 2017 and 2018), and Scottsbluff (PAN in 2018), NE.

broadleaf species (99% and 73%) in 2016 and 2017, respectively. Similarly, there were also more broadleaf species (77%) than grasses (23%) during the 2017 growing season at SCAL.

Average weed density at HAL in 2015 was 21 plants m^{-2}, with green foxtail [*Setaria viridis* (L.) P. Beauv.] being the dominant species (83% of the overall weed population). Common waterhemp [*Amaranthus tuberculatus* (Moq.) J. D.Sauer] accounted for 12% of the weed population. Other weed species were velvetleaf (*Abutilon theophrasti* Medik.), redroot pigweed (*Amaranthus retroflexus* L.), and ivyleaf morningglory (*Ipomoea hederacea* Jacq.), each accounting for <3% of the overall population (Table 3). Weed density at HAL in 2016 was much lower (4 plants m^{-2} on average) due to a dry spring (Table 3). In contrast, the highest weed density among location-years, averaging 29 plants m^{-2}, was observed at HAL in 2017 (Table 3).

During the 2017 growing season, the SCAL location had an average weed density of 16 plants m^{-2}. The three dominant weed species were green foxtail (23%), common waterhemp (21%), and Palmer amaranth (*Amaranthus palmeri* S. Watson) (17%). Other weed species belonging to the genus *Amaranthus* accounted for 20% of the overall weed population. Velvetleaf and common lambsquarters (*Chenopodium album* L.) accounted for 12% and 6%, respectively, of the overall population. In 2018 at SCAL, the prominent species were Palmer amaranth (30%), velvetleaf (26%), and green foxtail (24%). At PAN, the weed composition was 65%, 30%, and 5% for common lambsquarters, Palmer amaranth, and stintgrass [*Eragrostis cilianensis* (All.) Vignolo ex Janch.], respectively.

Soybean yield components

There was a significant impact of weed removal timing on soybean yield components: plants per square meter, pods per plant, and seeds per pod (Figure 1; Table 4). Application of PRE herbicides prevented significant reduction in soybean plants per square meter and seeds per pod, even with delayed weed removal. For example, at HAL in 2017, there was an average of 29 soybean plants m^{-2} in weed-free plots. Delaying weed removal until the R2 soybean stage (758 GDD) reduced the number to 26 soybean plants m^{-2} in plots without PRE herbicides. Weed interference throughout the growing season (weedy season-long) without PRE herbicide further reduced soybean plants to 20 plants m^{-2}. In addition, at SCAL in 2017, there was an average of 28 soybean plants m^{-2} in weed-free plots. Delaying weed removal until R2 soybean stage (505 GDD) significantly reduced the number to 17 soybean plants m^{-2} in plots without PRE herbicide. Soybean plants were significantly reduced to 12 plants m^{-2} when weeds interfered throughout the growing season without PRE herbicide (Figure 1; Table 4). Similar results were observed at SCAL and PAN in 2018 (Figure 1).

Table 4. Regression parameters showing the slope (*B*), lower limit (*C*), upper limit (*D*), and growing degree days (GDD) at 50% reduction (I_{50}) of different soybean yield components for no PRE and PRE herbicide applications in 2017 at Concord (HAL) and Clay Center (SCAL), NE.

			Regression parameters (±SE)			
Site	Yield components	PRE herbicide	*B*	*C*	*D*	I_{50} (GDD)
HAL	No. of plants m^{-2}	No PRE	3.3 (1.8)	13 (8)	29 (2)	1,343 (429)
		Saflufenacil + imazethapyr + pyroxasulfone	2.3 (1.1)	28 (8)	29 (9)	699 (154)
		Sulfentrazone + imazethapyr	1.5 (0.7)	28 (1)	27 (9)	850 (200)
	Pods per plant	No PRE	4.6 (1.5)	12 (2)	45 (2)	419 (85)
		Saflufenacil + imazethapyr + pyroxasulfone	2.8 (1.5)	31 (3)	46 (4)	259 (169)
		Sulfentrazone + imazethapyr	11.5 (4.7)	32 (1)	45 (1)	237 (45)
	Seeds per pod	No PRE	34.2 (9.1)	2.2 (0.1)	2.7 (0.1)	808 (85)
		Saflufenacil + imazethapyr + pyroxasulfone	1.1 (0.4)	2.6 (0.1)	2.8 (0.1)	98 (51)
		Sulfentrazone + imazethapyr	12.8 (2.4)	2.7 (0.1)	2.8 (0.1)	350 (124)
SCAL	No. of plants m^{-2}	No PRE	1.5 (0.8)	9 (4)	28 (1)	1,112 (278)
		Saflufenacil + imazethapyr + pyroxasulfone	8.6 (0.2)	14 (3)	29 (3)	2076 (49)
	Pods per plant	No PRE	2.4 (0.9)	0 (0)	42 (3)	517 (92)
		Saflufenacil + imazethapyr + pyroxasulfone	4.8 (1.4)	35 (4)	43 (4)	302 (113)
	Seeds per pod	No PRE	1.6 (0.8)	0 (0)	2.2 (0.1)	755 (154)
		Saflufenacil + imazethapyr + pyroxasulfone	0.1 (0)	2.2 (0.1)	2.3 (0.4)	6 (2)

On average, there were 45 and 41 pods per plant in weed-free plots, respectively for the HAL and SCAL locations in 2017. At HAL, delaying weed removal until R2 soybean stage (758 GDD) significantly reduced the pod count to 14 pods per plant in plots without PRE herbicides, while in plots with PRE herbicide (saflufenacil + imazethapyr + pyroxasulfone or sulfentrazone + imazethapyr), the pod counts was reduced to 32 pods per plant. At the same location, weed interference throughout the growing season without PRE herbicide resulted in 11 pods per plant, whereas application of any of the PRE herbicides minimized pod reduction, with 32 pods per plant. At SCAL, delaying weed removal until R2 soybean stage (505 GDD) reduced the pod count to 25 pods per plant in plots without PRE herbicide, whereas application of PRE herbicide (saflufenacil + imazethapyr + pyroxasulfone) prevented pod reduction, despite weed removal being delayed until R2. At the same location, weeds interfering throughout the growing season resulted in a very low pod count (3 pods per plant) without the PRE herbicide, while there was no significant reduction in pods in plots with PRE application of herbicide (Figure 1; Table 4). In 2018, the average numbers of pods per plant in weed-free plots were 45 and 62 at SCAL and PAN, respectively. There was a significant reduction in the number of pods in plots with season-long weed interference at both locations, with or without PRE application of herbicides, with the greatest reduction occurring in plots without PRE herbicides (Figure 1).

The number of seeds per pod was reduced for delayed weed removal timing without PRE application of herbicides. At all locations, soybean in weed-free plots produced approximately 3 seeds per pod. Weed interference throughout the growing season without PRE herbicide resulted in approximately 2 seeds per pod (Figure 1).

These results suggest that season-long weed interference without PRE application of herbicides negatively affected the soybean yield components with subsequent impact on the harvested yield. Previous studies have demonstrated that the impact of weed interference on crop yield could be explained by its impact on yield components (Adigun et al. 2014; Eaton et al. 1976; Elezovic et al. 2012; Trezzi et al. 2015). Indeed, the reduced yield can be attributed to the reduction in plants per square meter, pods per plant, and seeds per pod caused by weed interference in this study.

Soybean yield loss

Soybean yields decreased with increased delay in weed removal. Greater yield losses were observed in plots without PRE herbicides compared with plots with PRE herbicides. There were statistical differences in yield loss by location-year; thus, data are presented separately. In 2015, weed interference throughout the soybean-growing season (weedy season-long) resulted in 92% soybean yield loss in plots without application of PRE herbicide compared with 24% yield loss in plots with PRE herbicide (Figure 2; Table 5). Yield losses were lower in 2016 compared with other years of study, irrespective of whether PRE herbicide was applied or not (Figure 2; Table 5). Even without PRE application of herbicide, weed interference throughout the growing season caused relatively less yield loss of 45% compared with other years. Weedy season-long plots with PRE application of herbicides resulted in 14% to 16% soybean yield loss.

In 2017, the SCAL location had greater yield losses compared with the HAL location in plots with and without PRE treatments. At HAL, weedy season-long plots had yield loss up to 86% without PRE herbicide application, whereas application of saflufenacil plus imazethapyr plus pyroxasulfone or sulfentrazone plus imazethapyr as PRE herbicides in weedy season-long plots resulted in 13% yield loss. At SCAL, weedy season-long plots had up to 93% in yield loss without PRE herbicide application compared with 25% yield loss when PRE herbicide was applied. In 2018 at SCAL and PAN, weedy season-long plots had ≥94% yield loss. At SCAL, yield loss in weedy season-long plots was up to 60% with the application of PRE herbicides, while at PAN, application of PRE herbicides minimized yield loss to 9%.

Critical time for weed removal

The CTWR was estimated based on 5% yield loss. In 2015, the CTWR started at 226 GDD (21 DAE; V2 soybean stage) without PRE herbicide, while PRE application of herbicide (sulfentrazone + imazethapyr) delayed the CTWR to 374 GDD (35 DAE; V5 soybean stage) (Figure 2; Table 5). This implies that the CTWR was delayed by 14 d. In 2016, the commencement of the CTWR was later in the season than is usually expected for soybean. The CTWR started at 361 GDD (29 DAE; V6 soybean stage) without PRE herbicide application, while PRE application of saflufenacil plus imazethapyr plus pyroxasulfone or sulfentrazone plus

Table 5. Regression parameters and estimation of critical time for weed removal (CTWR) for no PRE and PRE herbicide applications.

			Regression parameters (SE)[a]			CTWR[b]		
Site	Herbicide application	Year	B	D	I_{50}	GDD (SE)	DAE	SGS
				%	GDD			
HAL	No PRE	2015	−3.6 (0.5)	92 (5)	610 (21)	226 (6)	21	V2
		2016	−2.2 (1.5)	45 (24)	723 (46)	361 (75)	37	V6
		2017	−5.9 (2.4)	77 (4)	466 (24)	156 (27)	14	V1
	Saflufenacil + imazethapyr + pyroxasulfone	2016	−3.2 (1.3)	20 (11)	952 (59)	843 (69)	66	R5
		2017	−0.7 (0.3)	11 (4)	677 (243)	324 (126)	28	V4
	Sulfentrazone + imazethapyr	2015	−1 (0.2)	24 (9)	845 (61)	374 (59)	35	V5
		2016	−2.6 (1)	15 (5)	918 (169)	639 (58)	50	R1
		2017	−1 (0.1)	19 (4)	952 (145)	395 (97)	35	V5
SCAL	No PRE	2017	−1.3 (0.7)	94 (62)	453 (53)	102 (16)	16	V1
		2018	−2.7 (1.2)	96 (23)	654 (39)	228 (10.6)	18	V2
	Saflufenacil + imazethapyr + pyroxasulfone	2017	−2.7 (1.8)	25 (11)	716 (194)	316 (101)	34	V6
		2018	−2.8 (0.5)	60 (13)	921 (74)	533 (43)	56	R2
PAN	No PRE	2018	−3.1 (1.3)	96 (5)	327 (34)	213 (45)	20	V2
	Saflufenacil + imazethapyr + pyroxasulfone	2018	−2.6 (1.4)	9 (3)	529 (27)	481 (64)	52	R1

[a] Parameters *B*, *D*, and I_{50} represent slope, maximum percentage yield loss, and growing degree days at 50% yield loss (GDD) respectively.
[b] The CTWR was estimated based on GDD at 5% yield loss. DAE, days after emergence; SGS, soybean growth stage

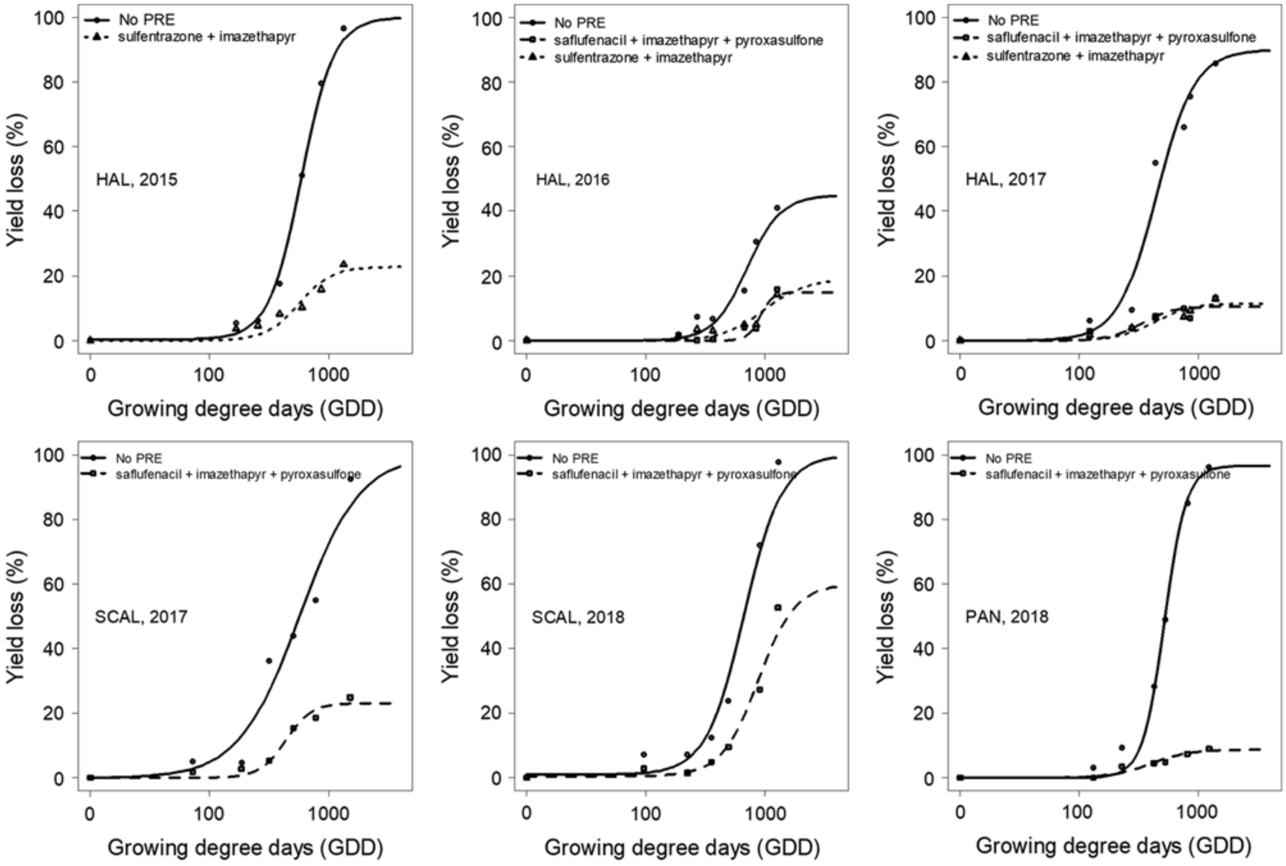

Figure 2. Soybean yield loss as a function of increasing delay of weed removal for no PRE and PRE herbicide applications at Concord (HAL in 2015, 2016, and 2017), Clay Center (SCAL in 2017 and 2018), and Scottsbluff (PAN in 2018), NE.

imazethapyr delayed the CTWR to 843 GDD (66 DAE; R5 soybean stage) or 639 GDD (50 DAE; R1 soybean stage), respectively (Figure 2; Table 5). Thus, with the application of PRE herbicides, the CTWR was delayed by 21 to 37 d.

In 2017 at HAL, the CTWR started at 156 GDD (14 DAE; V1 soybean stage) without PRE herbicide application, while the application of saflufenacil plus imazethapyr plus pyroxasulfone or sulfentrazone plus imazethapyr as PRE herbicides delayed the CTWR to 324 GDD (28 DAE; V4 soybean stage) or 395 GDD (35 DAE; V5 soybean stage), respectively (Figure 2; Table 5), suggesting that the CTWR was delayed by 14 to 21 d with PRE herbicides. At SCAL in 2017, the CTWR started at 102 GDD (16 DAE;

V1 soybean stage) without PRE herbicide application, while the application of PRE herbicide delayed the CTWR to 316 GDD (34 DAE; V6 soybean stage) (Figure 2; Table 5). This indicates that application of PRE herbicide delayed the CTWR by 18 d at SCAL. At both the SCAL and PAN locations in 2018, in plots without PRE herbicides, the CTWR started at 213 or 228 GDD, which was equivalent to V2 growth stage and 18 to 20 DAE. PRE application of herbicide delayed the CTWR to 533 GDD (56 DAE; R2 soybean stage) and 481 GDD (52 DAE; R1 soybean stage) at SCAL and PAN, respectively, resulting in a delay in CTWR by 28 to 34 d.

Management implications

The results from the different locations and years suggest that the length of time weed interference could be allowed in soybean without application of PRE herbicide ranged from 102 to 361 GDD, which was equivalent to the V1 (14 DAE) to V6 (37 DAE) soybean growth stages. With the application of PRE herbicides, the need for in-crop weed removal starts from 316 to 843 GDD, equivalent to the V4 (28 DAE) to R5 (66 DAE) soybean stages, depending on the study location and year. Similarly, previous studies have shown that the CTWR in soybean without PRE herbicide could range from 14 to 30 DAE (Gustafson et al. 2006; Knezevic et al. 2003; Van Acker et al. 1993), depending on the location of the study. Major factors that influenced CTWR and that varied with locations were weed density and time of weed emergence. The CTWR in crop fields with high weed density and early weed emergence is expected to occur earlier than in those locations with low weed density and late weed emergence (Jeschke et al. 2011; Kropff et al. 1987; Soltani et al. 2017). For example, in our study, without the influence of PRE herbicides, locations with high weed densities and early emergence of weeds had an earlier CTWR (V1 to V2 of soybean stage) compared with a location (HAL in 2016) with very low weed density and late weed emergence, resulting in an unusually late commencement of CTWR at V6.

Application of PRE herbicide delayed weed emergence and reduced density of weeds that could have competed with soybean and reduced yield. This study suggests that the use of PRE herbicides in GR soybean could delay the need for POST application of glyphosate by 14 to 34 d, thereby reducing the need for repeated applications of glyphosate, which is currently the usual practice during the growing season in a GR soybean. In addition, the use of PRE herbicides will provide multiple or alternative modes of action needed to manage GR weeds in GR soybean. It can be concluded that use of PRE herbicides in GR soybean could provide a window of 28 to 66 d after soybean emergence for POST weed removal. Otherwise, weed control without PRE herbicide application should be initiated 14 to 29 d after GR soybean emergence.

Author ORCIDs. O. Adewale Osipitan https://orcid.org/0000-0002-8202-4270

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References

Adigun J, Osipitan AO, Lagoke ST, Adeyemi RO, Afolami SO (2014) Growth and yield performance of cowpea (*Vigna unguiculata* (L.) Walp) as influenced by row-spacing and period of weed interference in south-west Nigeria. J Agric Sci 6:188–198

Beckie HJ, Harker KN (2017) Our top 10 herbicide-resistant weed management practices. Pest Manag Sci 73:1045–1052

Buhler DD, Liebman M, Obrycki JJ (2000) Theoretical and practical challenges to an IPM approach to weed management. Weed Sci 48:274–280

Eaton BJ, Russ OG, Feltner KC (1976). Competition of velvetleaf, prickly sida, and Venice mallow in soybeans. Weed Sci 24:224–228

Elezovic I, Datta A, Vrbnicanin S, Glamoclija D, Simic M, Malidza G, Knezevic SZ (2012) Yield and yield components of imidazolinone-resistant sunflower (*Helianthus annuus* L.) are influenced by pre-emergence herbicide and time of post-emergence weed removal. Field Crops Res 128:137–146

Evans SP, Knezevic SZ, Lindquist JL, Shapiro CA, Blankenship EE (2003) Nitrogen application influences the critical period for weed control in corn. Weed Sci 51:408–417

Gilmore EC, Rogers RS (1958) Heat units as a method of measuring maturity in corn. Agron J 50:611–615

Gustafson TC, Knezevic SZ, Hunt TE, Lindquist JL (2006) Early-season insect defoliation influences the critical time for weed removal in soybean. Weed Sci 54:509–515

Hall MR, Swanton CJ, Anderson GW (1992) The critical period of weed control in grain corn (*Zea mays*). Weed Sci 40:441–447

Heap I, Duke SO (2018) Overview of glyphosate-resistant weeds worldwide. Pest Manag Sci 74:1040–1049.

Jeschke MR, Stoltenberg DE, Kegode GO, Sprague CL, Knezevic SZ, Hock SM, Johnson GA (2011) Predicted soybean yield loss as affected by emergence time of mixed-species weed communities. Weed Sci 59:416–423

Knezevic SZ (2007) Herbicide tolerant crops: 10 years later. Maydica 52: 245–250

Knezevic SZ, Elezovic I, Datta A, Vrbnicanin S, Glamoclija D, Simic M, Malidza G (2013) Delay in the critical time for weed removal in imidazolinone-resistant sunflower (*Helianthus annuus*) caused by application of pre-emergence herbicide. Int J Pest Manag 59:229–235

Knezevic SZ, Evans SP, Blankenship EE, Van Acker RC, Lindquist JL (2002) Critical period of weed control: the concept and data analysis. Weed Sci 50:773–786

Knezevic SZ, Evans SP, Mainz M (2003) Row spacing influences the critical timing for weed removal in soybean (*Glycine max*). Weed Technol 17:666–673

Knezevic SZ, Osipitan OA, Scott JE (2018) Sensitivity of grape and tomato to micro-rates of dicamba-based herbicides. J Hort 5:1

Knezevic SZ, Streibig JC, Ritz C (2007) Utilizing R software package for dose-response studies: the concept and data analysis. Weed Technol 21:840–848

Kropff M, Joenje W, Bastiaans L, Habekotte B, van Oene H, Werner R (1987) Competition between a sugar beet crop and populations of *Chenopodium album* L. and *Stellaria media* L. Neth J Agric Sci 35:525–528

Odero DC, Wright AL (2013) Phosphorus application influences the critical period of weed control in lettuce. Weed Sci 61:410–414

Osipitan OA, Adigun JA, Kolawole RO (2016) Row spacing determines critical period of weed control in crop: cowpea (*Vigna unguiculata*) as a case study. Azarian J Agric 3:90–96

Owen MD (2016) Diverse approaches to herbicide-resistant weed management. Weed Sci 64:570–584

R Development Core Team 2017. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. http://www.R-project.org/. Accessed: August 2, 2017

Soltani N, Dille JA, Burke IC, Sikkema PH (2017) Perspectives on potential soybean yield losses from weeds in North America. Weed Technol 31:1–7

Teasdale JR (1995) Influence of narrow row/high population corn (*Zea mays*) on weed control and light transmittance. Weed Technol 9:113–118

Trezzi MM, Vidal RA, Patel F, Miotto E Jr, Debastiani F, Balbinot AA Jr, Mosquen R (2015). Impact of *Conyza bonariensis* density and establishment period on soyabean grain yield, yield components and economic threshold. Weed Res 55:34–41

Tursun N, Datta A, Budak S, Kantarci Z, Knezevic SZ (2016) Row spacing impacts the critical period for weed control in cotton (*Gossypium hirsutum*). Phytoparasitica 44:139–149

Van Acker RC, Swanton CJ, Weise SF (1993) The critical period of weed control in soybean [*Glycine max* (L.) Merr.]. Weed Sci 41:194–200