Soybean yield loss from delayed postemergence herbicide application based on weed height, days after emergence, accumulated crop heat units, and soybean growth stage

Authors: Soltani, Nader, Shropshire, Christy, and Sikkema, Peter H.

Source: Weed Technology, 36(3) : 403-408

Published By: Weed Science Society of America

URL: https://doi.org/10.1017/wet.2022.36

Weed Technology

www.cambridge.org/wet

Research Article

Cite this article: Soltani N, Shropshire C, Sikkema PH (2022) Soybean yield loss from delayed postemergence herbicide application based on weed height, days after emergence, accumulated crop heat units, and soybean growth stage. Weed Technol. **36**: 403–408. doi: 10.1017/wet.2022.36

Received: 24 January 2022
Revised: 29 March 2022
Accepted: 5 April 2022
First published online: 25 April 2022

Associate Editor:
Rodrigo Werle, University of Wisconsin

Nomenclature:
soybean; *Glycine max* (L.) Merr.

Keywords:
Soybean growth stage; accumulated crop heat units; days after crop emergence; early weed control; relative yield; weed size

Author for correspondence:
Nader Soltani, Department of Plant Agriculture, University of Guelph Ridgetown Campus, 120 Main St. East, Ridgetown, ON, Canada N0P 2C0.
Email: soltanin@uoguelph.ca

Soybean yield loss from delayed postemergence herbicide application based on weed height, days after emergence, accumulated crop heat units, and soybean growth stage

Nader Soltani[1], Christy Shropshire[2] and Peter H. Sikkema[3]

[1]Adjunct Professor, University of Guelph, Ridgetown, ON, Canada; [2]Research Technician, University of Guelph, Ridgetown, ON, Canada and [3]Professor, University of Guelph, Ridgetown, ON, Canada

Abstract

Limited information exists on the critical time of weed removal (CTWR) with the currently used soybean cultivars in Ontario. A study consisting of eight field experiments was conducted from 2017 to 2019 in Ontario, Canada, to determine the impact of delayed postemergence (POST) herbicide application on soybean yield based on average weed height at application, days after crop emergence (DAE), accumulated crop heat units (CHU) from the date of planting, and soybean growth stage. The regression model estimated the weed size at herbicide application that led to 1%, 2.5%, and 5% yield loss in soybean was 9, 14, and 20 cm under low weed density (averaging 73 to 134 plants m^{-2}) and 3, 4, and 6 cm under high weed density (143 to 153 plants m^{-2}) conditions, respectively. The estimated DAE at herbicide application time that led to 2.5%, 5%, 10%, and 25% yield loss in soybean was 24, 30, 37, and 53 DAE under low weed density and 8, 10, 14, and 23 DAE under high weed density, respectively. The predicted crop stage at herbicide application that resulted in 2.5%, 5%, 10%, and 25% yield loss in soybean was V4, V5, R2, and R5 under low weed density and VE, VC, V1, and V4 under high weed density, respectively. This study concludes that soybean yield loss is influenced by the weed density (low vs/high) and the time of the first POST herbicide application. When the first POST herbicide application was delayed until soybean was at the V2 stage the monetary loss was Can$20.46 and Can$221.20 ha^{-1} in low and high weed-density environments, respectively.

Introduction

Canada ranks seventh in global soybean production, producing nearly 6 billion kg in 2019 (Simpson 2020). Most of the soybean grown in Canada is produced in the province of Ontario (OMAFRA 2021). In 2020, growers in Ontario planted almost 1.12 million hectares and produced almost 3.6 billion kg of soybean with a farm-gate value of nearly Can$1.5 billion (OMAFRA 2021). Soybean has short physical stature that makes the crop vulnerable to weed interference. The yield loss committee of the Weed Science Society of America reported that if weeds are not controlled, soybean producers in the United States and Canada would lose an average of 52% of their soybean grain yield with a value of US$17.2 billion annually (Soltani et al. 2017).

Determining the critical weed-free period (CWFP) is necessary for developing weed management strategies in soybean crop production. The CWFP is defined as the duration of the crop life cycle during which if weeds are not controlled, irreversible crop losses occur (Zimdahl 1980). The beginning or the onset of the CWFP is determined using the critical time of weed removal (CTWR), whereas the end of the CWFP is the time in the growth of a crop when if weeds emerge after this time they do not have any impact on crop yield (Knezevic et al. 2002). Controlling weeds outside of the CWFP provides limited advantages in obtaining optimum crop yield (AAFC 2021). Controlling weeds during the CWFP can help improve the efficiency of weed management and reduce herbicide application needs (Van Acker et al. 1993). Determining the CWFP can also help avoid or reduce the unnecessary use of persistent herbicides in crops (Knezevic et al. 2002). The CWFP and CTWR can be determined based on a function of several factors including weed size, planting date, days after crop emergence (DAE), accumulated crop heat units (CHU) from emergence, crop growth stage, nitrogen application date, and other variables (Arslan et al. 2006; Bedmar et al. 1999; Eyherabide and Cendoya 2002; Halford et al. 2001; Mohammadi and Amiri 2011; Van Acker 1993).

Halford et al. (2001) reported that soybean needs to be kept weed-free from 13 to 44 DAE to avoid greater than 2.5% yield loss. Mohammadi and Amiri (2011) determined the CWFP for a <5% yield loss in soybean is 9 to 47 DAE. Van Acker (1993) determined that weeds need to be controlled by 30 DAE or the fourth node soybean stage (V4) to avoid greater than 2.5% yield loss. Zimdahl (1980) reported that weeds need to be controlled from 28 to 42 DAE to avoid significant yield losses in soybean. Other studies have also determined that weeds must not be present from the V2 to R1 stages to protect seed yield in soybean (Baysinger and Sims 1992; Fellows and Roeth 1992; Mulugeta and Boerboom 2000).

Most of the studies on the CWFP and CTWR in soybean were conducted more than two decades ago. Recent soybean cultivars have morphological traits that may reduce the impact of early weed interference, including rapid emergence and early growth, higher shoot biomass accumulation, increased plant height, and reduced time to flowering (Jannink et al. 2000; Place et al. 2011; Trezzi et al. 2013). The weed suppression ability of these new cultivars can affect the impact of early season weed interference and alter the CWFP, especially the onset of the CTWR (Place et al. 2011; Trezzi et al. 2013).

Most of the studies conducted in Ontario to determine the CWFP and specifically the CTWR were conducted with glyphosate-susceptible soybean cultivars; however, most growers in Ontario have transitioned to glyphosate-, glufosinate-, dicamba-, and/or 2,4-D-resistant cultivars over the past 25 yr (Gulden et al. 2009; Van Acker et al. 1993). The adoption of these new cultivars has shifted soybean cropping systems to earlier seeding time, increased seeding rates, narrow crop row width, and increased fertilization rates which can potentially alter the start (CTWR) and duration of the CWFP in soybean (Gulden et al. 2009). The early planting dates have also shifted the weed species community composition and density, which may have altered the CWFP. The prevalence of herbicide-resistant weeds, including glyphosate-resistant weeds in recent years, may have also changed weed community composition and the onset and duration of the CWFP, and the CTWR, in soybean (Gulden et al. 2009).

Limited information exists on the CTWR with the currently used soybean cultivars in Ontario. Information on the onset of CWFP is critically necessary because it allows soybean producers to implement timely weed management tactics to avoid significant yield losses. The objective of this study was to determine the CTWR in soybean with postemergence (POST) herbicides under low and high weed interference environments based on weed size, DAE, accumulated CHU from planting, and soybean growth stage.

Materials and Methods

The study consisted of eight field experiments conducted in Ontario near Exeter in 2017, 2018, and 2019, and Ridgetown in 2017, 2018a, 2018b, 2019a, and 2019b, in fields with common weeds in Ontario. Common weed species in Ontario include common lambsquarters (*Chenopodium album* L.), pigweeds (*Amaranthus* spp.), common ragweed (*Ambrosia artemisiifolia* L.), wild mustard (*Sinapis arvensis* L.), smartweed (*Polygonum scabrum* Moench.), eastern black nightshade (*Solanum ptycanthum* Dun.), wild buckwheat (*Polygonum convolvulus* L.), ladysthumb (*Polygonum persicaria* L.), velvetleaf (*Abutilon theophrasti* Medic.), barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv], and foxtails (*Setaria* spp.). The soil at Exeter was a Brookston clay loam (Orthic Humic Gleysol, mixed, mesic, and poorly drained), and the soil at the Ridgetown location was a Watford/Brady sandy loam. Seedbed preparation in all experiments consisted of fall moldboard plowing followed by two passes with a field cultivator with rolling basket harrows in the spring.

The experiment was a randomized complete block design with four replications. Plots were 3 m wide and 10 m long at Exeter and 8 m long at Ridgetown, and included four rows of soybean (glyphosate/dicamba-resistant; DKB 10-01/DKB 06-61/DKB 12-57) seeded in rows spaced 75 cm apart at approximately 400,000 seed ha^{-1} in May of each year. All experiments were fertilized according to recommended Ontario soybean production practices.

Treatments included a weedy control, a weed-free control, and six POST treatments in which the first herbicide application (glyphosate) was made when weeds were up to 5, 10, 15, 20, 30, and 50 cm in height. The planned experimental trigger for herbicide applications was weed size, the average weed canopy height in a mixed weed population. No soil-applied herbicides were used. All treatments were maintained weed-free with sequential glyphosate applications or hand hoeing until harvest after the first herbicide application.

Glyphosate (900 g ae ha^{-1}) was applied with a CO_2-pressurized backpack sprayer calibrated to deliver 200 L ha^{-1} of water at 200 kPa. The boom was 1.5 m long with four nozzles (Hypro ULD120-02 nozzle tips; Sprayer Supplies, Cary, NC) spaced 0.5 m apart producing a spray width of 2.0 m.

Soybean was combined (two center rows) at harvest maturity using a small-plot combine; soybean seed weight and moisture content were recorded. Yields were adjusted to 13% seed moisture and converted to kilograms per hectare. The yield was converted to a percent of the weed-free control to standardize yield. The average soybean yield and price (2017 to 2019) in Ontario (OMAFRA 2019) was used to determine monetary loss when the first POST herbicide application is delayed based on weed size, DAE, accumulated CHU from planting, and soybean growth stage.

Data analysis was carried out using SAS v.9.4 software (SAS Institute Inc., Cary, NC), and the level of significance was set at $P<0.05$. The soybean yield relative to the weed-free control—the response variable—was regressed against initial herbicide application timing, expressed as four individual explanatory variables (EVARs): weed size, DAE, CHU accumulated from planting, or soybean growth stage. Weed size was not measured after the last application, and therefore, the relative yield of the weedy control could not be included for this EVAR. DAE was the difference in days between soybean emergence and each application date; the weed-free control was given a value of 0, and the weedy control, reflecting the presence of weeds season-long, was represented by the number of days to reach harvest maturity. The accumulated CHU from planting date to each application date was determined from daily data obtained from the nearest weather station, and the weedy control was assigned a CHU corresponding to the cultivar maturity rating. The crop stage was recorded at the time of each application, and each stage was assigned a numerical value: 0 for the preemergence application on the weed-free control, 1 for VE, and up to 15 for R8, corresponding to the weedy control.

Prior to regression analysis, scatterplots of the data were examined to determine potential models, and a four-parameter log-logistic model was selected. Based on the scatterplots, it appeared that two environments differed from the other six environments in their yield response. One difference between the two groups of environments was the overall weed density: six environments had lower weed densities, ranging from 22 to 175 plants m^{-2} at individual application timings and averaging 73 to 134 plants m^{-2} for the season, while the other two environments had higher weed densities,

Table 1. Parameter estimates and predicted values for relative soybean yield regressed against initial herbicide application timing.[a]

EVAR	Group	Parameter estimates[b] (±SE)								ME	RMSE	Predicted EVAR value[c]					
		C		*D*		*b*		I_{50}				YL_1	$YL_{2.5}$	YL_5	YL_{10}	YL_{25}	YL_{50}
Weed size (cm)	LD	99	(1)	91	(1)	3.9	(2.3)	19	(3)	0.88	5.2	9	14	20	–	–	–
	HD	100	(2)	55	(13)	1.6	(0.6)	21	(9)	0.92	6.7	3	4	6	10	25	–
DAE	LD	99	(1)	58	(2)	4.6	(1.4)	49	(5)	0.79	6.7	–	24	30	37	53	–
	HD	101	(2)	30	(3)	2.5	(0.5)	28	(2)	0.91	6.5	6	8	10	14	23	41
CHUpl	LD	100	(1)	50	(12)	3.3	(1.1)	1,761	(446)	0.79	6.6	513	703	891	1,147	1,761	–
	HD	101	(2)	30	(3)	3.0	(0.5)	888	(46)	0.91	6.6	281	338	407	509	742	1,207
Crop stage[d]	LD	99	(1)	0	(0)	3.9	(0.4)	17	(0)	0.79	6.7	–	6	7	9	12	–
	HD	101	(2)	0	(0)	1.8	(0.2)	10	(0)	0.90	7.2	1	1	2	3	6	10

[a]Abbreviations: CHUpl, accumulated crop heat units from the date of planting; DAE, days after crop emergence; EVAR, explanatory variable; HD, high weed density; LD, low weed density; ME, modeling efficiency; RMSE, root-mean-square error.
[b]Log-logistic equation parameters (Equation 1): *b*, slope; *C*, upper asymptote; *D*, lower asymptote; I_{50}, EVAR value required for 50% response.
[c]YL_1, $YL_{2.5}$, YL_5, YL_{10}, YL_{25}, and YL_{50} are the values of an EVAR that result in a 1%, 2.5%, 5%, 10%, 25%, or 50% loss in soybean yield relative to the season-long weed-free control. A dash (-) or double dash (–) indicates the value in question was non-estimable because the asymptote was reached prior to that particular level of yield loss or the estimated values lie outside the range of values evaluated, respectively.
[d]Sequential numeric values assigned to vegetative and reproductive soybean stages: 0 = preemergence, 1 = VE . . . 7 = V5, 15 = R8.

ranging from 104 to 178 plants m^{-2} at individual application timings and averaging 143 to 153 plants m^{-2} for the season. Using the Glimmix procedure, the environment by EVAR interactions was used to measure the consistency in response for all environments combined, and for the two groups of environments separately. With all environments pooled, P-values for the interaction ranged from <0.0001 to 0.007, indicating that responses were not consistent among environments. However, P-values for the interaction ranged from 0.066 to 0.65 when the two groups of environments were separated, indicating a more consistent response within each group. To further confirm, corrected Akaike information criterion (AICc) values were calculated and compared for all environments pooled versus environments separated into the two groups; for all EVARs, AICc values were substantially lower for the latter scenario.

Regression analysis was carried out using the NLIN procedure, and residual plots were checked to make sure the assumptions of the analysis were met. The root-mean-square error (RMSE) and modeling efficiency (ME), as well as plots of actual versus predicted values were used to assess goodness of fit for the model evaluated. The log-logistic model used to regress relative soybean yield against herbicide application timing expressed as each EVAR, was:

$$Y = C + (D - C)/(1 + \exp[-b(\ln \text{EVAR} - \ln \text{I}_{50})]) \quad [1]$$

where *C* is the upper asymptote, *D* is the lower asymptote, *b* is the slope and I_{50} is the value of an EVAR, which gives a response halfway between *C* and *D*. Predicted values of each EVAR that gave a 1%, 2.5%, 5%, 10%, 25%, and 50% reduction in yield, relative to the weed-free control were calculated using the regression equations.

Results and Discussion

The weed size at the application time that led to a 1%, 2.5%, and 5% yield loss in soybean relative to the season-long weed-free control was 9, 14, and 20 cm, respectively, when weed density was low (Table 1; Figure 1). In addition, weed size at application time that led to a 1%, 2.5%, 5%, 10%, and 25% yield loss in soybean relative to the season-long weed-free control was 3, 4, 6, 10, and 25 cm, respectively, when weed density was high (Table 1; Figure 1).

The DAE at application time that led to a 2.5%, 5%, 10%, and 25% yield loss in soybean relative to the season-long weed-free control was 24, 30, 37, and 53 DAE with low weed density (Table 1; Figure 2). However, the DAE at application time that led to a 1%, 2.5%, 5%, 10%, 25%, and 50% yield loss in soybean relative to the season-long weed-free control was 6, 8, 10, 14, 23, and 41 DAE, respectively, with high weed density (Table 1; Figure 2). In other studies, Van Acker et al. (1993), studying the CWFP of soybean, reported that the CTWR was from 9 to 38 DAE, but the end of CWFP was consistently at 25 DAE to avoid >2.5% soybean yield loss. Chhokar et al. (1995) found the CTWR for soybean to be 27 to 40 DAE, and the crop had to be kept weed-free for 45 DAE to obtain 97.5% grain yield. Halford et al. (2001) reported that soybean needs to be kept weed-free until 13 to 44 DAE to avoid >2.5% yield loss in soybean. Keramati et al. (2008) found that soybean needs to be maintained weed-free between 26 to 63 DAE to achieve maximum soybean yield. Mohammadi and Amiri (2011) using a fitting logistic and Gompertz equation determined the CWFP for a 5% yield loss in soybean to be 9 to 47 DAE.

The more accumulated CHU prior to application, the greater the yield loss. The CHU from planting at application time that led to a 1%, 2.5%, 5%, 10%, and 25% yield loss in soybean relative to the season-long weed-free control was 513, 703, 891, 1,147, and 1,761 CHU, respectively, from planting under low weed density conditions (Table 1; Figure 3). However, the CHU from planting at application time that led to a 1%, 2.5%, 5%, 10%, 25%, and 50% yield loss in soybean relative to the season-long weed-free control was 281, 338, 407, 509, 742, and 1,207 CHU, respectively, from planting under high weed density conditions (Table 1; Figure 3). In other studies, Arslan et al. (2006) calculated the CWFP to prevent 10% yield loss in soybean varies between 1,369 to 1,376 CHU, which is consistent with the CHU reported by Halford et al. (2001). Mohammadi and Amiri (2011) using a fitting logistic and Gompertz equation determined the CWFP for a 5% yield loss in soybean to be 11 to 743 CHU.

The crop stage that led to a 2.5%, 5%, 10%, and 25% yield loss in soybean relative to the season-long weed-free control was V4, V5, R2, and R5, respectively, with low weed density (Table 1; Figure 4). However, the crop stage that led to a 1%, 2.5%, 5%, 10%, 25%, and 50% yield loss in soybean relative to the season-long weed-free control was VE, VE, VC, V1, V4, and R3, respectively, with high weed density (Table 1; Figure 4). In other studies, Van Acker et al. (1993) reported that the beginning of CWFP was from the second node (V2) to the reproductive stage (R1), but the end of CWFP was

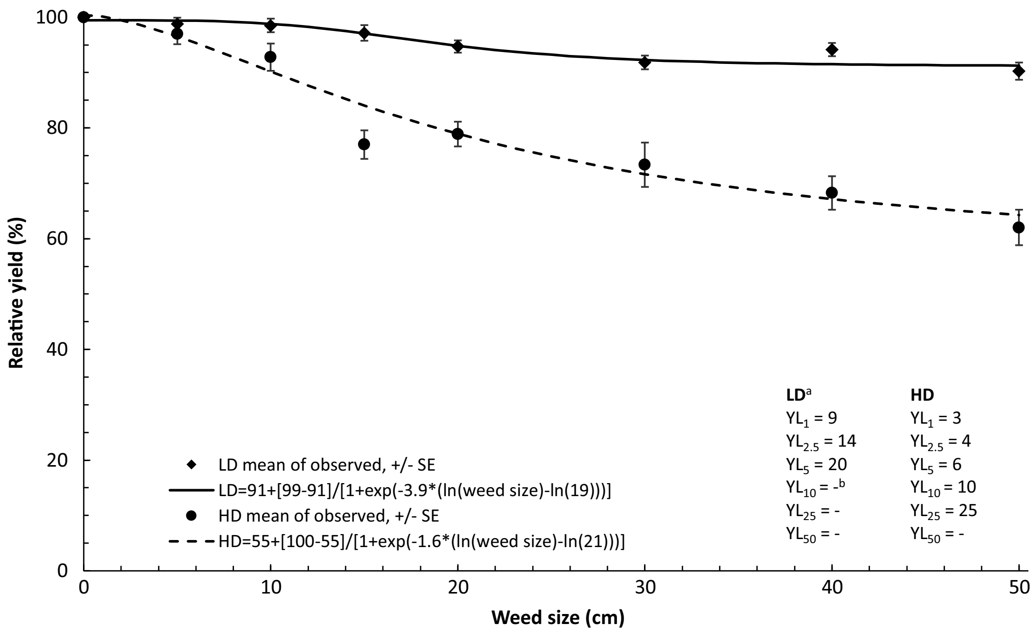

Figure 1. Relative soybean yield as a function of weed size at the time of herbicide application. Predicted regression lines were calculated using the log-logistic model (Equation 1). Low weed density (LD) modeling efficiency (ME) = 0.88, root-mean-square error (RMSE) = 5.2; high weed density (HD) ME = 0.92, RMSE = 6.7. [a]YL_1, $YL_{2.5}$, YL_5, YL_{10}, YL_{25}, and YL_{50} indicate weed size at the application that led to a 1%, 2.5%, 5%, 10%, 25%, and 50% yield loss in soybean relative to the season-long weed-free control. [b]Non-estimable.

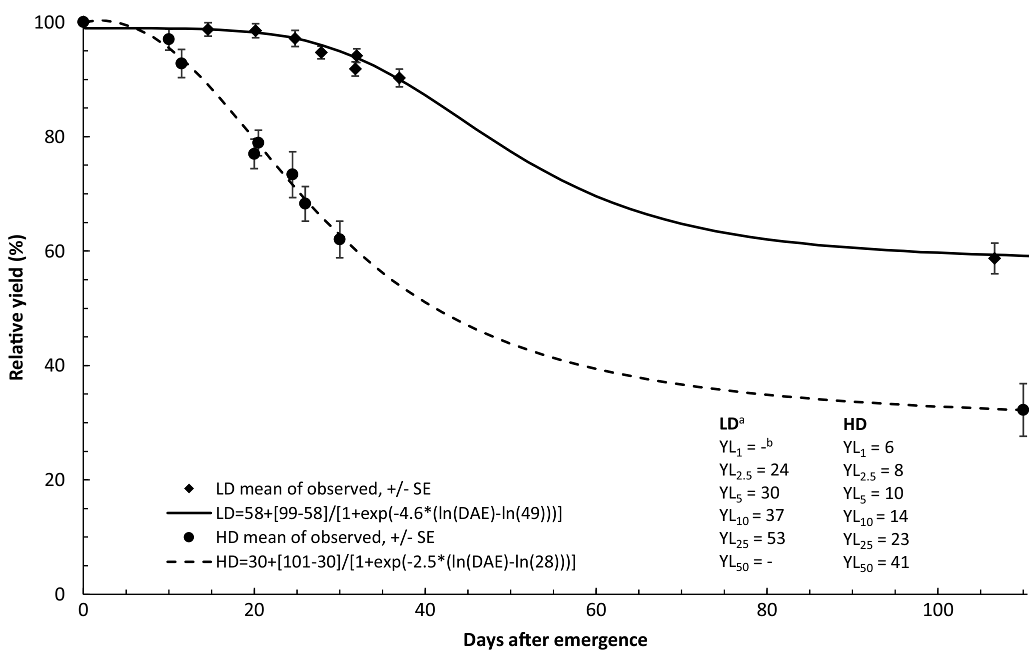

Figure 2. Relative soybean yield as a function of days after crop emergence (DAE) at the time of herbicide application. Predicted regression lines were calculated using the log-logistic model (Equation 1). Low weed density (LD) modeling efficiency (ME) = 0.79, root-mean-square error (RMSE) = 6.7; high weed density (HD) ME = 0.91, RMSE = 6.5. [a]YL_1, $YL_{2.5}$, YL_5, YL_{10}, YL_{25}, and YL_{50} indicate weed size at the application that led to a 1%, 2.5%, 5%, 10%, 25%, and 50% yield loss in soybean relative to the season-long weed-free control. [b]Non-estimable.

consistently at the fourth node stage (V4) to avoid >2.5% soybean yield loss in soybean. Eyherabide and Cendoya (2002) reported a CWFP of V2 to R1 to avoid significant yield losses in soybean. Halford et al. (2001) reported a CWFP of V1 to R1 to avoid greater than 2.5% yield loss in soybean. Similarly, Mohammadi and Amiri (2011) using a fitting logistic and Gompertz equation determined the CWFP for a 5% yield loss in soybean to be from the V1 to R1 stage in soybean growth. Keramati et al. (2008) also found that soybean needs to be kept weed-free from the V2 to R1 growth stages for maximum soybean yield.

Results of this study showed that the relative soybean seed yield decreased as the weed size, DAE, accumulated CHU from the

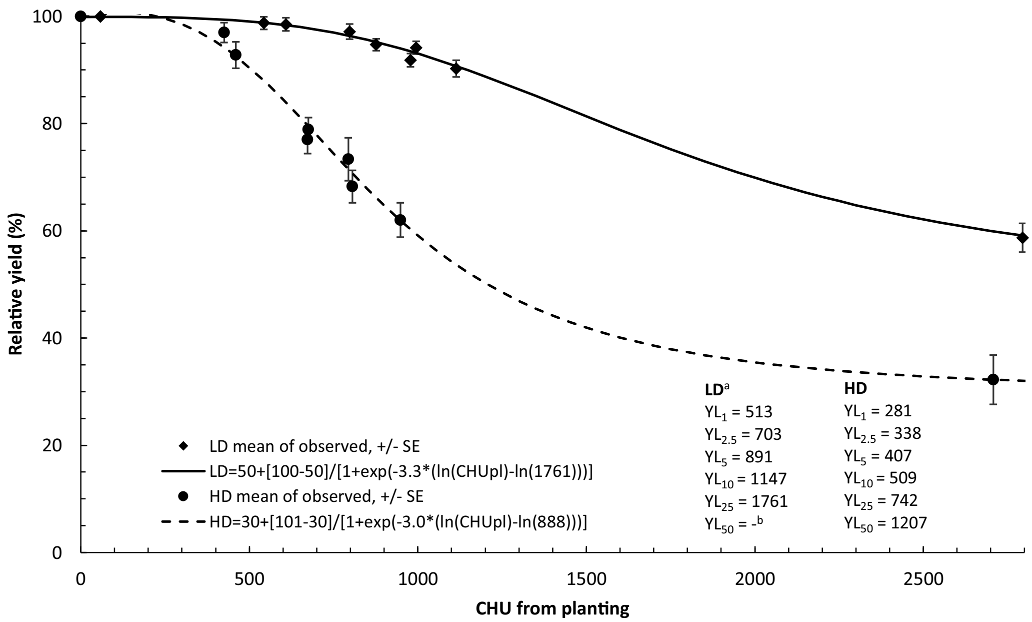

Figure 3. Relative soybean yield as a function of cumulative heat units (CHU) accumulated from planting at the time of herbicide application. Predicted regression lines were calculated using the log-logistic model (Equation 1). Low weed density (LD) modeling efficiency (ME) = 0.79, root-mean-square error (RMSE) = 6.6; high weed density (HD) ME = 0.91, RMSE = 6.6. [a]YL_1, $YL_{2.5}$, YL_5, YL_{10}, YL_{25}, and YL_{50} indicate weed size at the application that led to a 1%, 2.5%, 5%, 10%, 25%, and 50% yield loss in soybean relative to the season-long weed-free control. [b]Non-estimable.

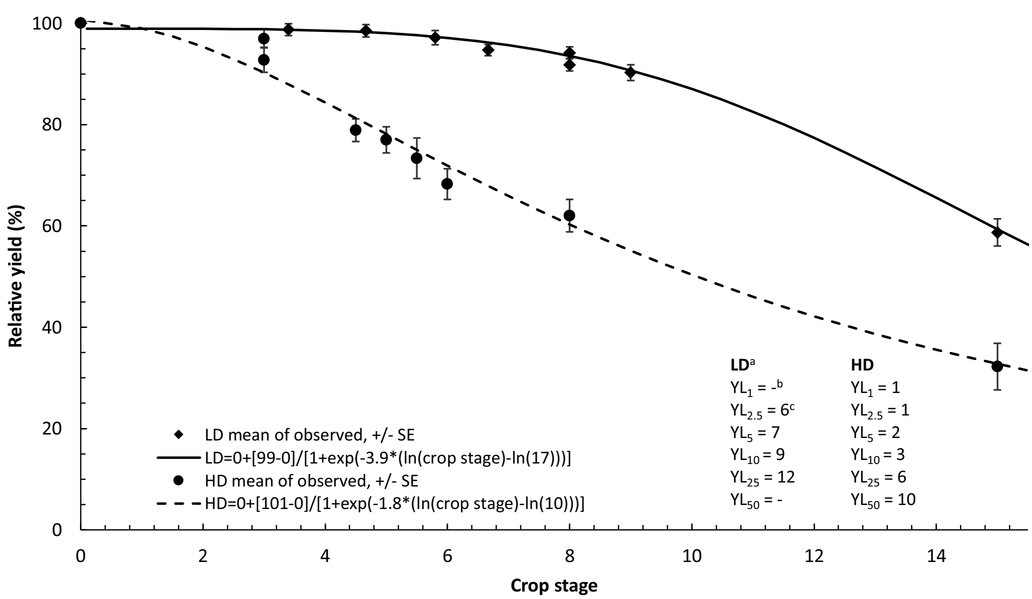

Figure 4. Relative soybean yield as a function of crop stage at the time of herbicide application. Predicted regression lines were calculated using the log-logistic model (Equation 1). Low weed density (LD) modeling efficiency (ME) = 0.79, root-mean-square error (RMSE) = 6.7; high weed density (HD) ME = 0.90, RMSE = 7.2. [a]YL_1, $YL_{2.5}$, YL_5, YL_{10}, YL_{25}, and YL_{50} indicate weed size at the application that led to a 1%, 2.5%, 5%, 10%, 25%, and 50% yield loss in soybean relative to the season-long weed-free control. [b]Non-estimable. [c]Sequential numeric values assigned to vegetative and reproductive soybean stages: 0 = preemergence, 1 = VE . . . 7 = V5, 15 = R8.

planting, and soybean growth stage increased before the first herbicide application. The CTWR was much earlier under higher weed density conditions compared to lower weed density conditions. To cause a 5% soybean seed yield loss, the average weed size was predicted to be 20 cm under low weed density and 6 cm under high weed density. The number of days that led to a 5% yield reduction in soybean was 30 DAE under low weed density and only 10 DAE under high weed density. Similarly, the accumulated CHU from planting that led to a 5% yield reduction in soybean was 891 CHU from planting under low weed density and only 407 CHU from planting under high weed density. If the weeds were not controlled until V4, V5, R2, and R5 stages, the data predict that there would be a 2.5%, 5%, 10%, and 25% reduction in soybean yield, respectively, under low weed density conditions. However, when the weed density was high, the data predict that soybean yield can be reduced by 1%, 2.5%, 5%, 10%, 25%, and 50% if weeds are not controlled at Ve, VE, VC, V1, V4, and R3 stages, respectively. These results indicate that soybean is sensitive to early weed interference and the importance of timely POST herbicide application. Weeds must be controlled before they reach 20 cm in height, prior to 30 d after crop emergence, prior to 891 accumulated CHU from emergence, or prior to the V5 soybean growth stage under a low weed density environment to avoid >5% soybean seed yield loss. Additionally, weeds must be controlled before they reach 6 cm in height, prior to 10 DAE, prior to 407 accumulated CHU from planting, or prior to the VC soybean growth stage under a high weed density environment to avoid >5% soybean seed yield loss. The average soybean yield and price in Ontario (2017 to 2019) was 3,170 kg ha^{-1} and Can$446.17 ha^{-1} (OMAFRA 2019). When the first POST herbicide was applied when weeds were an average of 5 cm in height in the low and high density environments the monetary loss was Can$8.55 and Can$49.28 ha^{-1}, respectively; when the first application was delayed until 10 DAE the monetary loss was Can$15.31 and Can$66.15 ha^{-1}, respectively; when the first application was delayed until 400 accumulated CHU after planting the monetary loss was Can$7.26 and Can$66.48 ha^{-1}, respectively; and when the first application was delayed until V2 the monetary loss was Can$20.46 and Can$221.20 ha^{-1}, respectively. This study concludes that the soybean yield and monetary loss can be substantial when the first postemergence herbicide application is delayed in high weed density environments.

Acknowledgments. Funding for this project was provided in part by the Grain Farmers of Ontario and the Ontario Ministry of Agriculture, Food, and Rural Affairs. No other conflicts of interest have been declared.

References

Agriculture and Agri-Food Canada (2021) Weed management options which reduce pesticide risk. https://umanitoba.ca/outreach/naturalagriculture/weed/files/herbicide/critical_period_e_print.htm. Accessed: February 11, 2022

Arslan ME, Uremis I, Uludag A (2006) The critical period of weed control in double-cropped soybean. Phytoparasitica 34:159–166

Baysinger JA, Sims BD (1992) Giant ragweed (*Ambrosia trifida*) interference in soybean (*Glycine max*). Weed Sci 39:358–362

Bedmar F, Manetti P, Monterubbianesi G (1999) Determination of the critical period of weed control in corn using a thermal basis. Pesqui Agropecu Bras 34:188–193

Chhokar RS, Balyan RS, Pahuja SS (1995) The critical period of weed competition in soybean [*Glycine max* (L.) Merrill]. Indian J Weed Sci 27:197–200

Eyherabide J, Cendoya M (2002) Critical periods of weed control in soybean for full-field and in-furrow interference. Weed Sci 50:162–166

Fellows GM, Roeth FW (1992) Shattercane (*Sorghum bicolor*) interference in soybean (*Glycine max*). Weed Sci 40:68–73

Gulden RH, Sikkema PH, Hamill AS, Tardif F, Swanton CJ (2009) Conventional vs. glyphosate resistant cropping systems in Ontario: weed control, diversity, and yield. Weed Sci 57:665–672

Halford C, Hamill AS, Zhang J, Doucet C (2001) Critical period of weed control in no-till soybean (*Glycine max*) and corn (*Zea mays*). Weed Technol 15: 737–744

Jannink JL, Orf JH, Jordan NR, Shaw RG (2000) Index selection for weed suppressive ability in soybean. Crop Sci 40:1087–1094

Keramati S, Pirdashti H, Esmaili MA, Abbasian A, Habibi M (2008) The Critical Period of Weed Control in Soybean (*Glycine max* (L.) Merr.). Pak J Biological Sci 1:463–467

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

Mohammadi GR, Amiri F (2011) Critical period of weed control in soybean (*Glycine max*) as influenced by starter fertilizer. Aust J Crop Sci 5:1350–1355

Mulugeta D, Boerboom CM (2000) Critical time of weed removal in glyphosate-resistant *Glycine max*. Weed Sci 48:35–42

[OMAFRA] Ontario Ministry of Agriculture and Food and Rural Affairs (2019) Average weekly soybean prices. weeklysoybeanprice.xlsx (live.com). Accessed: February 20, 2022

[OMAFRA] Ontario Ministry of Agriculture and Food and Rural Affairs (2021) Area, Yield, Production and Farm Value of Specified Field Crops, Ontario, 2012–2021. http://www.omafra.gov.on.ca/english/index.html. Accessed: May 5, 2022

Place GT, Reberg-Horton SC, Dickey DA, Carter TE Jr (2011) Identifying soybean traits of interest for weed competition. Crop Sci 51:2642–2654

Simpson V (2020) Largest Soybean-Producing Countries. World Facts. https://www.worldatlas.com/articles/largest-soybean-producing-countries.html. Accessed: May 20, 2022

Soltani N, Dille JA, Burke IC, Everman WJ, VanGessel MJ, Davis VM, Sikkema PH (2017) Perspectives on potential soybean yield losses from weeds in North America. Weed Technol 31:148–154

Trezzi MM, Balbinot AA Jr, Benin G, Debastiani F, Patel F, Miotto E Jr (2013) Competitive ability of soybean cultivars with horseweed (*Conyza bonariensis*). Planta Daninha 31:543–550

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

Zimdahl RL (1980) Pages 83–93 *in* Weed–Crop Competition. A review. Corvallis, OR: International Plant Propagators' Society