NRC Research Press

ARTICLE

The critical weed-free period in glyphosate-resistant soybean in Ontario is similar to previous estimates using glyphosate-susceptible soybean

Nader Soltani, Robert E. Nurse, Amit J. Jhala, and Peter H. Sikkema

Abstract: A study consisting of 13 field experiments was conducted during 2014–2016 in southwestern Ontario and southcentral Nebraska (Clay Center) to determine the effect of late-emerging weeds on the yield of glyphosate-resistant soybean. Soybean was maintained weed-free with glyphosate (900 g ae ha^{-1}) up to the VC (cotyledon), V1 (first trifoliate), V2 (second trifoliate), V3 (third trifoliate), V4 (fourth trifoliate), and R1 (beginning of flowering) growth stages, after which weeds were allowed to naturally infest the soybean plots. The total weed density was reduced to 24%, 63%, 67%, 72%, 76%, and 92% in Environment 1 (Exeter, Harrow, and Ridgetown) when soybean was maintained weed-free up to the VC, V1, V2, V3, V4, and R1 soybean growth stages, respectively. The total weed biomass was reduced by 33%, 82%, 95%, 97%, 97%, and 100% in Environment 1 (Exeter, Harrow, and Ridgetown) and 28%, 100%, 100%, 100%, 100%, and 100% in Environment 2 (Clay Center) when soybean was maintained weed-free up to the VC, V1, V2, V3, V4, and R1 stages, respectively. The critical weed-free periods for a 2.5%, 5%, and 10% yield loss in soybean were the V1–V2, VC–V1, and VC–V1 soybean stages in Environment 1 (Exeter, Harrow, and Ridgetown) and V2–V3, V2–V3, and V1–V2 soybean stages in Environment 2 (Clay Center), respectively. For the weed species evaluated, there was a minimal reduction in weed biomass (5% or less) when soybean was maintained weed-free beyond the V3 soybean growth stage. These results shows that soybean must be maintained weed-free up to the V3 growth stage to minimize yield loss due to weed interference.

Key words: biomass, density, glyphosate-resistant, growth stage, late-emerging weeds, soybean, yield.

Résumé : De 2014 à 2016, les auteurs ont poursuivi une étude composée de treize expériences sur le terrain dans le sud-ouest de l'Ontario et le centre-sud du Nebraska (Clay Center). L'objectif consistait à préciser les répercussions des adventices à germination tardive sur le soja résistant au glyphosate. Les parcelles de soja ont été désherbées avec du glyphosate (900 g de matière active par hectare) jusqu'aux stades VC (cotylédon), V1 (première feuille trifoliée), V2 (deuxième feuille trifoliée), V3 (troisième feuille trifoliée), V4 (quatrième feuille trifoliée) et R1 (début de la floraison), puis on a laissé les mauvaises herbes envahir naturellement la culture. Le glyphosate a respectivement ramené la densité des adventices à 24, 63, 67, 72, 76 et 92 % dans le premier environnement (Exeter, Harrow et Ridgetown) après application jusqu'aux stades VC, V1, V2, V3, V4 et R1. Quand le désherbage chimique se poursuit jusqu'aux stade VC, V1, V2, V3, V4 et R1, la masse totale de mauvaises herbes diminue respectivement de 33, 82, 95, 97, 97 et 100 % dans le premier environnement (Exeter, Harrow et Ridgetown) et de 28, 100, 100, 100, 100 et 100 % dans le second (Clay Center). La période durant laquelle le soja ne doit absolument pas subir la concurrence des mauvaises herbes si l'on ne veut pas que son rendement baisse de 2,5, de 5 ou de 10 % correspond respectivement à celle des stades V1–V2, VC–V1 et VC–V1 pour le premier environnement (Exeter, Harrow et Ridgetown) et V2–V3, V2–V3 et V1–V2 dans le second (Clay Center). Continuer le désherbage au-delà du stade V3 ne réduit la biomasse des adventices que marginalement (5 % ou moins). Les résultats de cette étude indiquent que, pour préserver le rendement potentiel du soja, la culture doit être désherbée jusqu'au stade de croissance V3. [Traduit par la Rédaction]

Mots-clés : biomasse, densité, résistance au glyphosate, stade de croissance, adventices tardives, soja, rendement.

Received 27 February 2018. Accepted 24 December 2018.

N. Soltani and P.H. Sikkema. University of Guelph Ridgetown Campus, Ridgetown, ON N0P 2C0, Canada.

R.E. Nurse. Agriculture and Agri-Food Canada, Harrow, ON N0R 1G0, Canada.

A.J. Jhala. University of Nebraska, Lincoln, NE 68583-0915, USA.

Corresponding author: Nader Soltani (email: soltanin@uoguelph.ca).

*A.J. Jhala currently serves as an Associate Editor; peer review and editorial decisions regarding this manuscript were handled by Robert Gulden.

Introduction

Soybean is a major crop in Ontario and Nebraska. From 2007 to 2013, on average, soybean growers in Ontario harvested 979 000 ha and produced 2.9 million tonnes of soybean valued at CAD$1.1 billion and growers in Nebraska harvested 1 046 000 ha and produced 3 million tonnes of soybean valued at CAD$1.2 billion (Soltani et al. 2017).

Currently, more than 79% of the soybean grown in Ontario and 95% of the soybean grown in Nebraska are glyphosate-resistant (GR) or glyphosate/dicamba-resistant cultivars (P.H. Sikkema and A. Jhala, personal communication). Glyphosate-resistant soybean is popular with growers in Ontario and Nebraska due to crop safety, broad-spectrum weed control, flexibility of application timing, environmental safety, and lower costs, which increases growers' competitiveness in the market place (Sikkema and Soltani 2007). Franz et al. (1997) and Dill et al. (2010) have reported that more than 300 weed species can be controlled with glyphosate applied after emergence (postemergence). Many soybean producers, including those in Ontario and Nebraska, apply glyphosate once or sequentially as their only weed management strategy in GR soybean production, despite its limitations (e.g., selection pressure for GR weeds) (Gonzini et al. 1999; Mulugeta and Boerboom 2000; Young 2006).

The critical weed-free period control has been defined as the crop stage beyond which irreversible yield losses occur if weeds are present in the field (Knezevic et al. 2002, 2003). Studies by Baysinger and Sims (1992), Fellows and Roeth (1992), and Mulugeta and Boerboom (2000) have shown that weeds need to be controlled between growth stages V2 and R1 to avoid yield losses in soybean. Glyphosate application timing needs to be strategically timed based on weed species composition, weed population, emergence timing of the weed and crop, and environmental conditions to avoid yield losses in GR soybean (Mulugeta and Boerboom 2000). Previous studies have reported that a single application of glyphosate in GR soybean can result in substantial yield loss due to weed emergence after application because glyphosate does not provide residual control of weeds (Gonzini et al. 1999; Nurse et al. 2007; Stewart et al. 2010). In contrast, other studies have found that a single application of glyphosate at the right time was sufficient to adequately control troublesome weeds with no soybean yield loss (Mulugeta and Boerboom 2000; Boerboom 2003), assuming no presence of GR weeds in the field.

Weed control is influenced by many factors including weed species, population, time of emergence, cultural practices, crop row spacing, time of crop emergence, nutrient availability, and environmental conditions (Zimdahl 1980; Di Tomaso 1995; Evans et al. 2003; Knezevic et al. 2003; Arslan et al. 2006; Mohammadi and Amiri 2011). Soybean cultivars released in recent years have provided new morphological characteristics that enables soybean crop to provide enhanced weed suppressive ability through greater aboveground biomass accumulation, enhanced early growth, increased plant height, and early flowering (Jannink et al. 2000; Place et al. 2011; Trezzi et al. 2013). These weed-suppressive soybean cultivars can decrease early weed pressure and provide in-season yield benefits for soybean production (Jannink et al. 2000). To our knowledge, there is a lack of information on the critical weed-free period to avoid yield losses in GR soybean under Ontario environmental conditions. An earlier study by Van Acker et al. (1993) determined the critical period for weed control in Ontario-grown soybeans, but was conducted nearly 25 yr ago. The study was done with glyphosate-susceptible soybeans and plots were maintained weed-free to various crop stages by hand-weeding. With the adoption of GR soybean production systems and the subsequent changes in cultural practices in Ontario, it is important to examine the effect of weeds that emerge late in the season on the yield of GR soybean. The recent adoption of soybean cultivars with enhanced weed-suppressive capabilities may have shifted the critical period for weed control in soybean. The introduction of herbicide-resistant weeds has also shifted weed communities in some Ontario fields (Gulden et al. 2009). Growers in Ontario often plant soybean earlier in the season than 25 yr ago and use lower seeding rates, as seed is one of the most expensive costs in GR soybean production. Row spacing has also changed, as many growers now prefer 75 cm row spacing for more uniform emergence and lower seed costs. Information on the effects of in-season emerging weeds on GR soybean yield can help growers choose when to effectively control weeds and increase their net profit. The objective of this study was to determine how long GR soybean needs to be kept weed-free to avoid yield losses due to weed interference in Ontario and Nebraska.

Materials and Methods

A study consisting of 13 field sites was conducted during 2014–2016 at Exeter (43.316305, −81.504763) (2014a and 2014b, 2015a and 2015b, and 2016a and 2016b), Harrow (42.034920, −82.902318) (2015 and 2016), and Ridgetown (42.444594, −81.883203) (2014, 2015, and 2016) in Ontario, and Clay Center (40.820744, −96.700470) (2015 and 2016) in Nebraska. Seedbed preparation at all sites consisted of fall moldboard plowing followed by two passes with a field cultivator with rolling basket harrows in the spring. The cultivation depth was approximately 10 cm at all study sites.

Experiments were arranged in a randomized complete block design with four replications. Treatments included soybean maintained weed-free with glyphosate (Roundup Weathermax®, Monsanto, St. Louis, MO) at 900 g ae ha^{-1} up to the VC (cotyledon), V1 (first trifoliate), V2 (second trifoliate), V3 (third trifoliate), V4 (fourth trifoliate), and R1 (beginning of flowering) growth stages. Additional treatments consisted of an untreated weedy control and a weed-free control that was maintained with hand-weeding/hoeing as needed. Each plot was 3 m wide and 8 or 10 m long depending on the research site and consisted of four rows of soybean seeded 0.75 m apart. Glyphosate-resistant soybean cultivars ('DKB 27-60RY' or '30-61 RY') were seeded 5 cm deep at a rate of 400 000 seeds ha^{-1} in May to early June. All plots were fertilized according to recommended Ontario crop production practices.

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) spaced 50 cm apart.

At 9 wk after crop emergence (WAE), weed species in two 0.25 m^{-2} quadrats (randomly placed) in each plot were counted by species, cut at the soil surface, placed in a paper bag, dried at 60 °C to a constant moisture, and then weighed. Soybean was harvested (the two center rows) at maturity using a plot combine. Yields were adjusted to 13% seed moisture and converted to kg ha^{-1}.

The PROC MIXED procedure in SAS (version 9.4; SAS Institute Inc., Cary, NC) was used to initially analyze all data. Relative yield, density, and biomass were subjected to analysis of variance. Variances were separated into the random effects of year and location, replication (at each location), and random effects by soybean maturity stage. The significance of the random effects, replication nested within environment (year × location), and their interaction with the fixed effect was tested using the Z test of the variance estimate. The assumptions of the variance analysis were tested by ensuring that the residuals were random, homogeneous, and with a normal distribution about a mean of zero using residual plots and the Shapiro–Wilk normality test. Relative yield data did not require transformation, while density and biomass data were log-transformed. Density and biomass data were pooled into environments based on the significance of the environment × treatment interaction. All density and biomass data are presented on the back-transformed scale. Mean separation was based on a least square difference (LSD) test at the 5% level.

Using PROC NLMIXED, relative yield data were then regressed against growing degree day (GDD) using a Gompertz equation: $Y = A \exp[-B \exp(-KT)]$, where Y was relative crop yield (% of weed-free control), A was the upper asymptote of yield, K and B were constants, and T was GDD. Growing degree days were calculated using daily temperature data (obtained from weather stations) from each site using a base of 10 °C in the formula: GDD= $[(\text{max daily } T + \text{min daily } T)/2) - 10]$. For ease of estimating the critical weed-free period, soybean growth stage was superimposed over GDD for each environment. Initial estimates of the regression parameters were made using an iterative process and the upper asymptote (A) was estimated to be 100, which was the theoretical maximum value for yield. The NLMIXED procedure was then used to test the lack of difference among regression parameters (among environments) using single degrees of freedom contrasts (Knezevic et al. 2002). The degrees of freedom for the parameters were calculated using the equation $df = (N_i - 1) - P_i$, where N_i is the total number of non-missing observations used and P_i is the number of parameters to be estimated for the ith model (Knezevic et al. 2002). Regression data were pooled into environments based on a comparison of these parameters.

Results and Discussion

Studies were separated based on two different environments (Fig. 1). Environment 1 combined studies conducted at Exeter (2014a, 2014b, 2015a, 2015b, 2016a and 2016b); Harrow (2015 and 2016), and Ridgetown (2014, 2015, and 2016); and Environment 2 was Clay Center (2015 and 2016).

Weed control

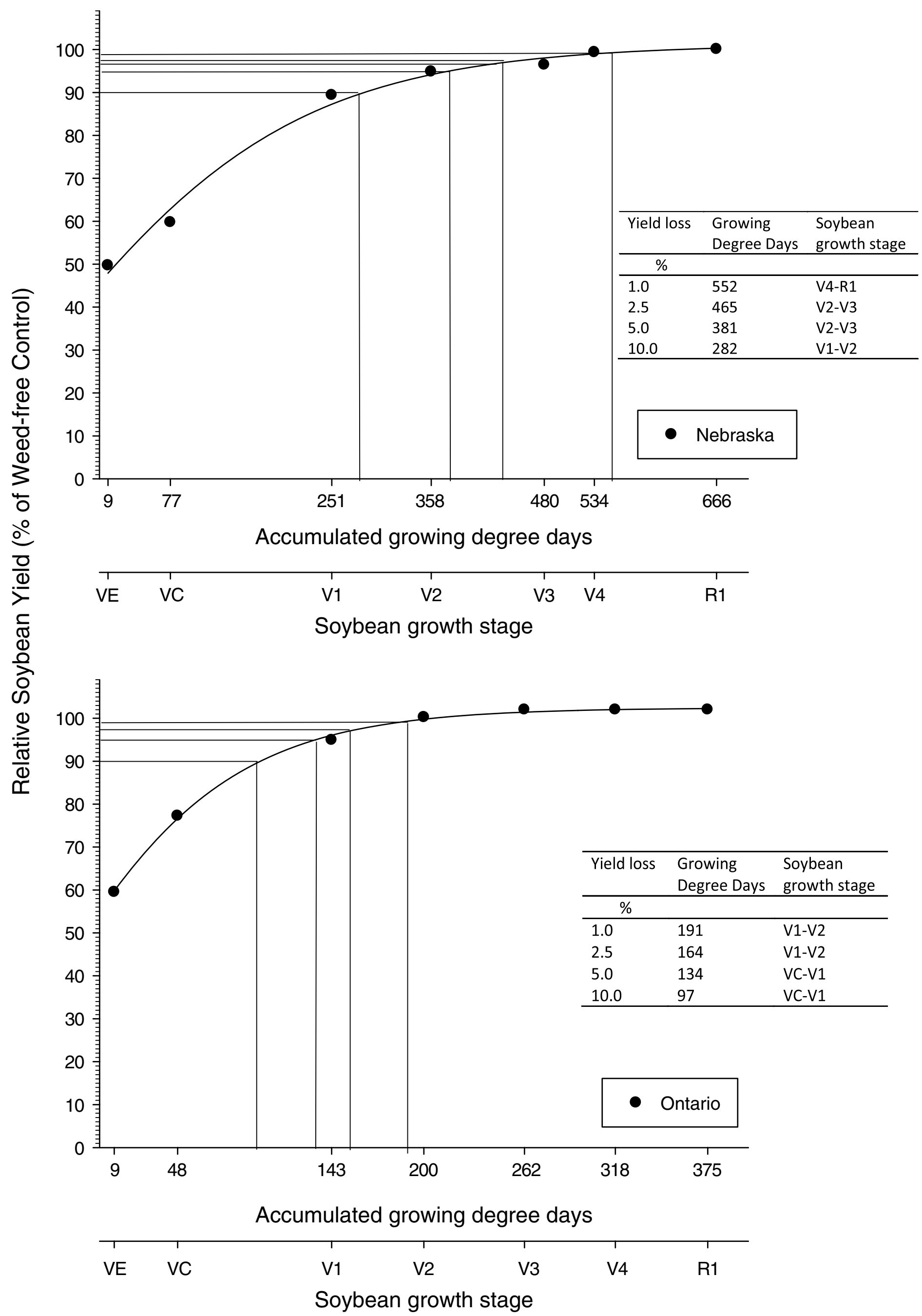
In Exeter, total weed density and biomass within the untreated control plots were 109 ± 4 plants m^{-2} and 189 ± 7 g m^{-2}, respectively (Tables 1 and 2). Weed species composition (based on density) within the untreated control plots included 32% green foxtail [*Setaria viridis* (L.) Beauv.] and 31% wild mustard (*Sinapis arvensis* L.). Untreated control plots also included 15% common lambsquarters (*Chenopodium album* L.), 9% flower-of-an-hour (*Hibiscus trionum* L.), 7% redroot pigweed (*Amaranthus retroflexus* L.), 3% smartweed [*Persicaria lapathifolia* (L.) Gray], 2% wild buckwheat (*Polygonum convolvulus* L.), 2% ladysthumb (*Polygonum persicaria* L.), and 1% barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] (Table 1).

In Harrow, the total weed density and biomass within the weedy control plots were 258 ± 13 plants m^{-2} and 543 ± 19 g m^{-2}, respectively (Table 1). Weed species composition (based on density) within the weedy control plots included 45% large crabgrass [*Digitaria sanguinalis* (L.) Scop.], 27% stinkgrass [*Eragrostis cilianensis* (All.) Janch.], 10% common lambsquarters, 10% barnyardgrass, 3% redroot pigweed, 3% ladysthumb, 2% common ragweed (*Ambrosia artemisiifolia* L.), 1% eastern black nightshade (*Solanum ptychanthum* Dun.), and <1% witchgrass (*Panicum capillare* L.).

In Clay Center, the most prominent weed species present at the study site (visual observation) were velvetleaf (*Abutilon theophrasti* Medik.), Palmer amaranth (*Amaranthus palmeri* Wats.), and giant foxtail (*Setaria faberi* Herrm.) (data not shown).

In Ridgetown, the total weed density and biomass within the weedy control plots were 125 ± 7 plants m^{-2} and 242 ± 13 g m^{-2}, respectively (Table 1). The weed species composition (based on density) consisted of 37% green

Fig. 1. Influence of the weed-free period on soybean yield at (A) Nebraska and (B) Ontario between 2014 and 2016. The interaction between year and weed-free period was not significant; therefore data were not separated by year. Relative yield data were regressed against weed-free period using a Gompertz equation: $Y = A \exp[-B \exp(-KT)]$, where Y is relative crop yield (% of weed-free control), A is the upper asymptote of yield, K and B are constants, and T is growing degree days. The parameter estimates were: (A) $a = 101$, $b = 150$, and $k = -34$ and (B) $a = 102$, $b = 63$, and $k = -30$ for Nebraska and Ontario, respectively. VE, emergence (untreated control); VC, cotyledon; V1, first trifoliate; V2, second trifoliate; V3, third trifoliate; V4, fourth trifoliate; and R1, start of flowering.



foxtail, 28% barnyardgrass, 19% common lambsquarters, 10% velvetleaf, 5% common ragweed, and 2% green pigweed within the weedy control plots (Table 1).

Weed pressure was lower when soybean was kept weed-free for a greater duration (Table 2). The total weed density was reduced by 24%, 63%, 67%, 72%, 76%, and 92% at Environment 1 (Exeter, Harrow, and Ridgetown) when soybean was maintained weed-free up to the VC, V1, V2, V3, V4, and R1 soybean growth stages, respectively (Table 2). Total weed biomass was reduced by 33%, 82%, 95%, 97%, 97%, and 100% in Environment 1 (Exeter, Harrow, and Ridgetown) and 28%, 100%, 100%,

Table 1. Total weed density, biomass, and species composition within untreated control plots at Exeter, Harrow, and Ridgetown, ON, and Clay Center, NE.

Location	Total density (No. m^{-2})	Total biomass (g m^{-2})	Weed species	Proportion of density (%)	Proportion of biomass (%)
Exeter	109 ± 4.2	189.2 ± 6.9	*Amaranthus retroflexus*	7	8
			Chenopodium album	15	21
			Echinochloa crus-galli	1	1
			Hibiscus trionum	9	3
			Polygonum convolvulus	2	2
			Polygonum persicaria	2	7
			Polygonum scabrum	3	2
			Setaria viridis	32	33
			Sinapis arvensis	31	24
Harrow	258 ± 13.1	542.7 ± 19.4	*Amaranthus retroflexus*	3	3
			Ambrosia artemisiifolia	2	17
			Chenopodium album	10	17
			Digitaria sanguinalis	45	35
			Echinochloa crus-galli	10	11
			Eragrostis cilianensis	27	7
			Panicum capillare	0	3
			Polygonum persicaria	3	4
			Solanum ptychanthum	1	3
Ridgetown	125 ± 6.9	242.3 ± 12.6	*Abutilon theophrasti*	10	6
			Amaranthus powellii	2	1
			Ambrosia artemisiifolia	5	24
			Chenopodium album	19	9
			Echinochloa crus-galli	28	29
			Setaria viridis	37	30

Note: Collections were made 9 wk after crop emergence. Weed density and biomass values are followed by the standard error of the mean.

100%, 100%, and 100% in Environment 2 (Clay Center) when soybean was maintained weed-free up to the VC, V1, V2, V3, V4, and R1 stages, respectively (Table 2). Differences between environments can be attributed to variations between weed communities present at each environment. In Environment 1, the prominent weed species consisted of common lambsquarters, wild mustard, common ragweed, barnyardgrass, large crabgrass, stinkgrass, and green foxtail. In Environment 2, however, the most prominent weed species present were velvetleaf, Palmer amaranth, and giant foxtail.

The results of this study are consistent with previous studies about the critical weed-free period and soybean yield loss. For instance, Van Acker et al. (1993), in a study that was conducted in Ontario, reported that if soybean was kept weed-free until the V1 to V2 growth stage, weed biomass and density were 30% and 25%, respectively, of the weedy control. However, if the soybean was kept weed-free until the V3 growth stage, weed biomass and density were only 3% and 8% of the weedy control, respectively. Similarly, Murphy and Gossett (1981), in a study conducted in South Carolina, reported that weed biomass was reduced as much as 97% compared to the weedy control if soybean had no weeds until 3 WAE. Murphy and Gossett (1981) found no additional reduction in weed dry weight biomass or weed density if soybean was kept weed-free beyond the V3 growth stage. Mulugeta and Boerboom (2000) reported that glyphosate applied at the V2, V4, and R1 stages can provide as much as a 100% reduction in the biomass of weeds at study sites in Wisconsin, which were predominantly common lambsquarters, velvetleaf, Pennsylvania smartweed (*Polygonum pensylvanicum* L.), and giant foxtail.

Soybean yield

The critical weed-free period for 2.5%, 5%, and 10% yield loss in soybean were the V1–V2, VC–V1, and VC–V1 soybean stages in Environment 1 (Exeter, Harrow, and Ridgetown) and the V2–V3, V2–V3, and V1–V2 soybean stages in Environment 2 (Clay Center), respectively (Fig. 1). Likewise, Van Acker et al. (1993) found that if soybean is kept weed-free up to the V4 stage (about 30 d after emergence), soybean yield loss can be kept under 3%. Mulugeta and Boerboom (2000) found that to protect seed yield in GR soybean, weeds need to be removed between the V2 and V4 stages. Yield reduction was as low as 3% when soybean was kept weed-free up to the V4 stage (Mulugeta and Boerboom 2000). Chokar and Balyan (1999) found that soybean need to

Table 2. Total weed density and biomass at soybean maturity stages ranging from the untreated control to R1 at Ontario, Canada, and Nebraska, USA.

Location	Soybean maturity stage	Total density[a] (No. m^{-2})	Total biomass (g m^{-2})
Ontario	Weedy control	164a	324.7b
	VC	125a	216.6b
	V1	60b	59.5c
	V2	54b	17.4c
	V3	46b	10.6cd
	V4	40b	8.9d
	R1	13c	0.7d
Nebraska	Weedy control	—	709a
	VC	—	513a
	V1	—	1d
	V2	—	2d
	V3	—	0d
	V4	—	0d
	R1	—	0d

Note: Data were combined due to a non-significant environment × treatment interaction. Data followed by the same lowercase letters within a column are not different according to an LSD test at $p > 0.05$. Soybean maturity dates: VC, cotyledon; V1, first trifoliate; V2, second trifoliate; V3, third trifoliate; V4, fourth trifoliate; and R1, start of flowering.

[a]Weed density data from Clay Center, NE, was not collected.

be kept weed-free 30–45 d after seeding for optimum soybean yield. The authors also found no differences in the predicted yield if weeds were removed before 35 d after soybean emergence or at the V4 soybean growth stage. In contrast, Eyherabide and Cendoya (2002) found that soybean needs to be weed-free between the V2 and V8 soybean stages for optimum yield under Argentinian environmental conditions. They also reported that to avoid yield losses of 2.5% and 10%, soybean needs to be kept weed-free 50 and 61 d after emergence, respectively (Eyherabide and Cendoya 2002).

Many soybean producers are tempted to delay the postemergence application of glyphosate until the majority (or all) of the weeds have emerged. Although this does result in improved weed control at harvest, the hidden impact of early weed interference on crop yield can be substantial. The results of this study indicate that GR soybean must be kept free of weeds up to the V3 growth stage. There was a minimal (5% or less) reduction in weed biomass (dry weight) when soybean was kept weed-free beyond the V3 soybean growth stage for the weed species evaluated.

Conclusion

Glyphosate-resistant soybean must be kept free of weeds up to the V3 soybean growth stage for optimum yield. The critical weed-free period in GR soybean in Ontario was similar to previous estimates using glyphosate-susceptible soybean in Ontario. Weeds emerging after the V3 soybean growth stage did not affect the yield of GR soybean; however, growers must be warned that although soybean yield was not affected, weeds that emerge after the V3 soybean growth stage can potentially add weed seeds to the seedbank, interfere with harvest operations, and impact soybean grade at the point of sale. Also, allowing late-emerged weeds to reproduce goes against the principles of herbicide resistance weed management. A recent study by Norsworthy et al. (2012) stated that to reduce the risks of herbicide-resistant weeds, growers need to reduce weed seed return to the soil, especially from GR biotypes, by achieving near-perfect weed control in all fields in all years, as long as they are farming. Therefore, a season-long weed control program is needed to achieve long-term weed control in cropping systems.

Acknowledgements

Funding for this study was made possible through Grain Farmers of Ontario and the Growing Forward 2 program of the Agricultural Adaptation Council.

References

Arslan, M., Uremis, I., and Uludag, A., 2006. The critical period of weed control in double-cropped soybean. Phytoparasitica, **34**(2): 159–166. doi:10.1007/BF02981316.

Baysinger, J.A., and Sims, B.D. 1992. Giant ragweed (*Ambrosia trifida*) interference in soybeans (*Glycine max*). Weed Sci. **39**: 358–362.

Boerboom, C. 2003. Economics of residual herbicides in Roundup Ready crops. [Online]. Available from https://extension.soils.wisc.edu/wcmc/economics-of-residual-herbicides-in-roundup-ready-crops/.

Chokar, R.S., and Balyan, R.S. 1999. Competition and control of weeds in soybean. Weed Sci. **47**: 107–111.

Di Tomaso, J.M. 1995. Approaches for improving crop competitiveness through the manipulation of fertilization strategies. Weed Sci. **43**: 491–497.

Dill, G.M., Sammons, R.D., Feng, P.C.C., Kohn, F., Kretzmer, K., Mehrsheikh, A., Bleeke, M., Honegger, J.L., Farmer, D., and Wright, D. 2010. Glyphosate: discovery, development, applications, and properties. Pages 1–33 in V.K. Nandula, ed. Glyphosate resistance in crops and weeds: history, development, and management. John Wiley & Sons, Hoboken, NJ.

Evans, S.P., Knezevic, S.Z., Shapiro, C., and Lindquist, J.L. 2003. Nitrogen level affects critical period for weed control in corn. Weed Sci. **51**: 408–417. doi:10.1614/0043-1745(2003)051[0408:NAITCP]2.0.CO;2.

Eyherabide, J.J., and Cendoya, M.G. 2002. Critical period of weed control in soybean for full field and in-furrow interference. Weed Sci. **50**: 162–166. doi:10.1614/0043-1745(2002)050[0162:CPOWCI]2.0.CO;2.

Fellows, G.M., and Roeth, F.W. 1992. Shattercane (*Sorghum bicolor*) interference in soybean (*Glycine max*). Weed Sci. **40**: 68–73.

Franz, J.E., Mao, M.K, and Sikorski J.A. 1997. Glyphosate: a unique global herbicide. American Chemical Society, Washington, DC.

Gonzini, L.C., Hart, S.E., and Wax, L.M. 1999. Herbicide combinations for weed management in glyphosate-resistant soybean (*Glycine max*). Weed Technol. **13**: 354–360. doi:10.1017/S0890037X00041853.

Gulden, R.H., Sikkema, P.H., Hamill, A.S., Tardif, F., and Swanton, C.J. 2009. Conventional vs. glyphosate-resistant cropping systems in Ontario: weed control, diversity, and yield. Weed Sci. **57**: 665–672. doi:10.1614/WS-09-023.1.

Jannink, J.L., Orf, J.H., Jordan, N.R., and Shaw, R.G. 2000. Index selection for weed suppressive ability in soybean. Crop Sci. **40**: 1087–1094. doi:10.2135/cropsci2000.4041087x.

Knezevic, S.Z., Evans, S.P., Blankenship, E., VanAcker, R.C., and Lindquist, J.L. 2002. Critical period for weed control: the concept and data analysis. Weed Sci. **50**: 773–786. doi:10.1614/0043-1745(2002)050[0773:CPFWCT]2.0.CO;2.

Knezevic, S.Z., Evans, S.P., and Mainz, M. 2003. Row spacing influences the critical timing for weed removal in soybean (*Glycine max*). Weed Technol. **17**: 666–673. doi:10.1614/WT02-49.

Mohammadi, G.R., and Amiri, F. 2011. Critical period of weed control in soybean (*Glycine max*) as influenced by starter fertilizer. Aust. J. Crop Sci. **5**(11): 1350–1355.

Mulugeta, D., and Boerboom, C.M. 2000. Critical time of weed removal in glyphosate-resistant *Glycine max*. Weed Sci. **48**: 35–42. doi:10.1614/0043-1745(2000)048[0035:CTOWRI]2.0.CO;2.

Murphy, T.R., and Gossett, B.J. 1981. Influence of shading by soybeans (*Glycine max*) on weed suppression. Weed Sci. **29**: 610–615. doi:10.1017/S0043174500063839.

Norsworthy, J.K., Ward, S.M, Shaw, D.R., Llewellyn, R.S., Nichols, R.L., Webster, T.M., Bradley, K.W., Frisvold, G., Powles, S.B., Burgos, N.R., Witt, W.W., and Barret, M. 2012. Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci. **60**: 31–62. doi:10.1614/WS-D-11-00155.1.

Nurse, R.E., Hamill, A.S., Swanton, C.J., Tardif, F.J., Deen, W., and Sikkema, P.H. 2007. Is the application of a residual herbicide required prior to glyphosate application in no-till glyphosate-tolerant soybean (*Glycine max*)? Crop Prot. **26**: 484–489. doi:10.1016/j.cropro.2006.04.018.

Place, G.T., Reberg-Horton, S.C., Dickey, D.A., and Carter, T.E., Jr. 2011. Identifying soybean traits of interest for weed competition. Crop Sci. **51**: 2642–2654. doi:10.2135/cropsci2010.11.0654.

Sikkema, P.H., and Soltani, N. 2007. Herbicide-resistant crops in eastern Canada. Pages 3–13 in R.H. Gulden and C.J. Swanton, eds. The first decade of herbicide-resistant crops in Canada. Topics in Canadian Weed Science. Vol. 4. Canadian Weed Science Society, Sainte-Anne-de-Bellevue, QC.

Soltani, N., Dille, J.A., Burke, I.C., Everman, W.J., VanGessel, M.J., Davis, V.M., and Sikkema, P.H. 2017. Perspectives on potential soybean yield losses from weeds in North America. Weed Technol. **31**: 148–154. doi:10.1017/wet.2016.2.

Stewart, C.L., Nurse, R.E., Hamill, A S., and Sikkema, P.H. 2010. Environment and soil conditions influence pre- and postemergence herbicide efficacy in soybean. Weed Technol. **24**: 234–243. doi:10.1614/WT-09-009.1.

Trezzi, M.M., Balbinot, A.A., Jr., Benin, G., Debastiani, F., Patel, F., and Miotto, E., Jr. 2013. Competitive ability of soybean cultivars with horseweed (*Conyza bonariensis*). Planta Daninha, **31**: 543–550. doi:10.1590/S0100-83582013000300006.

Van Acker, R.C., Swanton, C.J., and Wiese, S.F. 1993. The critical period of weed control in soybean [(*Glycine max*) (L.) Merr.]. Weed Sci. **41**: 194–200.

Young, B.G. 2006. Changes in herbicide use patterns and production practices resulting from glyphosate-resistant crops. Weed Technol. **20**: 301–307. doi:10.1614/WT-04-189.1.

Zimdahl, R.L. 1980. Weed-crop competition (a review). International Plant Protection Control, Oregon State University, Corvallis, OR. pp. 83–93.