Canadian Journal of Plant Science
Revue canadienne de phytotechnie

**Weed control, environmental impact, and net revenue of
two-pass weed management strategies in dicamba-
resistant soybean**

Journal:	<i>Canadian Journal of Plant Science</i>
Manuscript ID	CJPS-2017-0147.R2
Manuscript Type:	Article
Date Submitted by the Author:	24-Aug-2017
Complete List of Authors:	Underwood, Matthew; University of Guelph, Ridgetown Campus Soltani, Nader; University of Guelph, Ridgetown Campus Robinson, Darren; University of Guelph, Dept. Plant Agriculture Hooker, David; University of Guelph Ridgetown Campus,, Plant Agriculture; University of Guelph Swanton, Clarence; University of Guelph, Plant Agriculture Vink, Joseph; Monsanto Canada Inc, Sikkema, Peter; University of Guelph, Dept. Plant Agriculture
Keywords:	Dicamba, dicamba-resistant, glyphosate, herbicide resistance, soybean, yield, weeds

SCHOLARONE™
Manuscripts

Weed control, environmental impact, and net revenue of two-pass weed management strategies in dicamba-resistant soybean

Matthew G. Underwood, Nader Soltani, Darren E. Robinson, David C. Hooker, Clarence J. Swanton, Joseph P. Vink, and Peter H. Sikkema

Abstract: Six field trials were conducted over a two-year period (2014, 2015) at two locations in southwestern Ontario to compare the level of weed control provided by dicamba applied alone and in combination with dimethenamid-p applied preemergence (PRE) in glyphosate/dicamba-resistant soybean to current industry standards when used in a two-pass weed management program. Crop injury, weed control, soybean seed yield, environmental impact (EI), and profitability were evaluated in this study. No significant injury was documented. Several PRE herbicides provided excellent early season grass and broadleaved weed control, though early season weed control of those weed species was not acceptable with glyphosate applied alone or in combination with dicamba, dicamba plus dimethenamid-p, 2,4-D, or saflufenacil applied PRE. At 8 weeks after application, the sequential application of a PRE herbicide followed by

Received 1 May 2017, accepted XX XX 2017.

M.G. Underwood, N. Soltani, D.C. Hooker, D.E. Robinson, and P.H. Sikkema. University of Guelph Ridgetown Campus, Ridgetown, ON N0P 2C0, Canada.

Joseph P. Vink. Monsanto Canada Inc., 900 - One Research Road, Winnipeg, Manitoba, R3T 6E3, Canada.

C.J. Swanton. Department of Plant Agriculture, University of Guelph, Guelph, ON N1G 2W1, Canada.

Corresponding author: Nader Soltani (e-mail: soltanin@uoguelph.ca).

Abbreviations: GR, glyphosate-resistant; fb, followed by; WAA, weeks after application; POST, post-emergence; PRE, pre-emergence.

glyphosate applied postemergence (POST) provided at least 86% control of weed species evaluated in this study. Weed interference with no herbicide treatments caused a soybean seed yield loss of 64%. The sequential application of glyphosate had the lowest EI value. The addition of chlorimuron plus metribuzin or chlorimuron plus imazethapyr did not increase the EI substantially, but did improve the level of weed control and reduced weed density and biomass. The inclusion of a PRE herbicide in a weed management program also has several stewardship benefits and may reduce the selection for herbicide resistant weeds.

Key words: Dicamba, dicamba-resistant, glyphosate, herbicide resistance, soybean, yield, weeds

Introduction

Soybean (*Glycine max* (L.) Merr.) is one of the most important grain crops produced in Ontario, Canada. In 2015, soybean was grown on 1.2 million hectares across Ontario producing over 3.6 million tonnes of soybean valued at nearly \$1.6 billion (Kulasekera, 2016). Weed management is a critical component of successful soybean production in the province.

To maximize soybean yield the crop must be maintained weed free during the critical weed free period (CWFP). The CWFP varies depending on the relative time of weed and crop emergence, weed species composition and density, soybean row spacing, and soybean seeding rate. Assuming a yield loss of 5% is acceptable, the CWFP in soybean begins at V1 and ends at V4 (Knezevic et al. 2003; Mulugeta and Boerboom, 2000). Failure to control weeds during the CWFP can reduce soybean yield by as much as 80% (Halford et al. 2001).

Because glyphosate does not provide residual weed control, sequential applications of glyphosate in GR soybean may be required during the CWFP to achieve acceptable weed control

(Gonzini et al. 1999; Nurse et al. 2006; Stewart et al. 2011). The repeated use of a herbicide with a single mode of action may select for herbicide-resistant (HR) weed biotypes and is therefore not recommended (Nurse et al. 2006). Two-pass weed management strategies of an effective herbicide(s) applied pre-plant (PP) or preemergence (PRE) with residual activity, followed by an in-crop postemergence (POST) herbicide, frequently results in excellent full-season weed control (Gonzini et al. 1999; Soltani et al. 2012). Full season control minimizes soybean yield loss due to weed interference and reduces selection pressure for HR weed biotypes.

Glyphosate/dicamba-resistant (DR) soybean will be available for commercial use in Canada for the first time in 2017. Dicamba is a systemic broadleaved herbicide that is active on many broadleaved weed species including several GR weed species found in Canada including Canada fleabane (*Conyza canadensis* (L.) Cronq.), giant ragweed (*Ambrosia trifida* L.), common ragweed (*Ambrosia artemisiifolia* L.) and waterhemp (*Amaranthus rudis* J.D.Sauer). In addition, dicamba provides control of GR weed species not currently found in Canada including Palmer amaranth (*Amaranthus palmeri* S.Wats.) (Johnson et al. 2010; Spaunhorst et al. 2014). The addition of the dicamba resistance gene in soybean will allow for an additional herbicide option for broadleaved weed control. Dicamba can be applied PP, PRE, or POST in DR soybean, making it attractive to use in a two-pass weed management program. There is little information on the efficacy of two-pass weed management in dicamba-resistant soybean.

Environmental impact (EI) should be considered when developing weed management programs (Gianessi, 2005; Brookes and Barfoot, 2015). One way to measure the environmental impact of a herbicide program is to determine the environmental impact quotient (EIQ). The EIQ has been used successfully in the past to compare the potential environmental risk of weed management programs (Brimner et al. 2005; Fernandez-Cornejo et al. 1998; Stewart et al. 2011;

Soltani et al. 2012). The risk is calculated based on toxicological and physiochemical factors among three main environmental components: the farmworker, consumer, and ecosystem (Kovach et al. 1992; Fernandez-Cornejo et al. 1998). Each component is then subdivided to reflect all facets that may be affected by the application of one or several active ingredients. Higher EI values identify chemicals that may have a greater risk of negatively impacting the environment. To our knowledge, no study has evaluated the environmental impact and profitability of two-pass weed management systems in no-till dicamba-resistant soybean.

The objectives of this study were to evaluate the crop injury, weed control, soybean yield, profitability, and EI of various two-pass weed management systems in no-till dicamba-resistant soybean.

Materials and Methods

Six field experiments were conducted over a two-year period (2014, 2015) in southwestern Ontario at two sites, the University of Guelph – Ridgetown Campus, Ridgetown, Ontario; and the Woodstock Research Station, Woodstock, Ontario. Data including seeding date, herbicide application dates, soybean growth stage, and weed densities and stages are presented in Table 1.

Experiments were conducted using a randomized complete block design with four replications. Each replicate included a weedy (untreated) and weed-free control. The weed-free plots were maintained weed-free throughout the growing season by applying a tank-mix of glyphosate (900 g ae ha⁻¹) plus imazethapyr (100 g ai ha⁻¹) plus metribuzin (400 g ai ha⁻¹) PRE, followed by glyphosate (900 g ae ha⁻¹) applied POST if required. A DR soybean cultivar was

seeded at 400 000 seeds ha⁻¹ in 4-row plots where the rows were spaced 0.76 m apart. Plots were 5.75 and 8 m long in Woodstock in 2014 and 2015, respectively, and 8 m long in Ridgetown.

Herbicides were applied with a CO₂ pressurized backpack sprayer calibrated to apply 200 L ha⁻¹ of aqueous solution at 210 kPa using a 1.5 m spray boom equipped with four ultra-low drift (ULD) 120-02 nozzles (Hypro, New Brighton, MN, USA) spaced 0.5 m apart. Glyphosate (Roundup WeatherMAX, Monsanto, St. Louis, MO, USA) applied at 900 g ae ha⁻¹ was added to all the PRE herbicides for the control of emerged weeds. A POST application of glyphosate (900 g ae ha⁻¹) was also made at the V4 soybean growth stage and represented the second herbicide application timing in the two-pass weed control programs evaluated.

The study was designed to compare the level of weed control provided by dicamba (XtendiMax[®] with VaporGrip[®] Technolog Herbicide 350 SL formulation, Monsanto) applied PRE on its own (600 g ae ha⁻¹) or in a tank-mix at 300 g ae ha⁻¹ with dimethenamid-p (544 g ai ha⁻¹) to DR soybean in a two-pass weed management system grown in a no-tillage environment to several current industry standards (Table 2).

Soybean injury was assessed visually at 2 and 3 weeks after emergence (WAE) on a scale of 0 (no injury) to 100 (complete soybean death). Weed control was assessed visually on a scale of 0 (no control) to 100 (complete control) at three WAE prior to the in-crop application of glyphosate, and four and eight weeks after the POST application of glyphosate weeks after application B (WAA_B). The species assessed included velvetleaf (*Abutilon theophrasti* Medik), common ragweed (*Ambrosia artemisiifolia*), redroot pigweed (*Amaranthus retroflexus* L.), common lambsquarters (*Chenopodium album* L.), barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.), and green foxtail (*Setaria viridis* (L.) P. Beauv.). At 3 WAE, weed density and dry

weight were determined by counting the number of weeds present within a 1 m² quadrat randomly placed within each plot. After counting, the weeds were cut at ground level, separated by species, and placed in paper bags and dried in a kiln at 60° C for one week and dry weights were recorded for each species. Soybean yield data were collected by harvesting the middle two rows of the four-row plots using a small plot combine. All yield data were adjusted to 13% moisture prior to analysis.

All data were subjected to ANOVA using the PROC MIXED procedure in SAS Version 9.4 (SAS Institute, Cary, NC). No significant interactions between environment and treatment were detected ($P > 0.05$) so data from all experiments were combined across years and locations. Variances were separated into fixed and random effects. Fixed effects included herbicide treatment while random variances were chosen to include environment (year and location), block nested within environment, and treatment by environment interaction so any treatment inferences made would be more broadly applicable than to just the six environments examined (Yang 2010). A P-value of $P < 0.05$ was used to determine the significance of the random and fixed effects when using a Z- and F-test, respectively. To confirm the assumptions of the ANOVA were met, PROC UNIVARIATE procedure was applied and confirmed using residual plots and a Shapiro-Wilk test for normality. All weed control data required an arcsine square root transformation, weed density and dry weight were transformed using a log transformation, and yield data did not require a transformation. All data were back-transformed to their original scale for presentation purposes and treatments were separated using Fisher's Protected LSD at $P < 0.05$.

The EI of each herbicide program was determined using EIQ values from Kovach et al. (1992, 2012). To calculate the EI for each herbicide treatment, the EIQ for each active ingredient (ai) was multiplied by the amount of ai applied, in kg ai ha⁻¹. All treatments included multiple

herbicide applications and many included multiple herbicide active ingredients. In the case of glyphosate, the EI was multiplied by two to account for the two herbicide applications, PRE and POST. The EI for each herbicide program is presented in Table 7.

A partial profit analysis was also conducted to determine the profitability of each herbicide program (Table 7). Gross profit was determined by multiplying plot yield by the average soybean price in Ontario for the month of October of each year (Blair Andrews, personal communication, 2016). Herbicide costs were calculated based on herbicide prices for each year reported by AGRIS (AGRIS Co-operative Ltd., 2015). Application costs were based on data reported by Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) in their annual Field Crop Budgets – Publication 60 annual publication (OMAFRA, 2016a). For products that weren't available for sale in 2014, the 2015 herbicide price was used; products that are not yet available on the market were excluded from the profit analysis. Data were analyzed using the PROC MIXED procedure mentioned above. A square root transformation was used on the data to satisfy the assumptions of the ANOVA.

Results and Discussion

Soybean Injury

No significant visible soybean injury (< 5%) was observed in this study (data not presented).

Weed Control

At 3 WAE, glyphosate (900 g ae ha⁻¹) applied PRE provided 32 to 54% and 14 to 15% broadleaved and grass control, respectively, prior to the in-crop application of glyphosate (Table

2). At 3 WAE, glyphosate (900 g ae ha⁻¹) plus saflufenacil (25 g ai ha⁻¹), dicamba (600 g ae ha⁻¹), dicamba (300 g ae ha⁻¹) plus dimethenamid-p (544 g ai ha⁻¹), or 2,4-D (500 g ae ha⁻¹) controlled broadleaves and grasses 58 to 79% and 13 to 69% respectively. Contrasting results were reported by Fausey and Renner (2001) who reported that dicamba provided 72% to 95% broadleaved weed control 8 WAA in corn (*Zea mays* L.). Norsworthy et al. (2009) found that dicamba provided limited residual control of Canada fleabane. Budd et al. (2016) found that an additional herbicide had to be added to saflufenacil (25 g ai ha⁻¹) for full season control of Canada fleabane. The lower weed control with 2,4-D, dicamba, and saflufenacil at the time of the POST application is likely due to the limited residual activity of these herbicides. A number of other studies have concluded that a PRE residual herbicide applied with a POST application of glyphosate provide effective control of late-emerging weeds (Gonzini et al. 1999; Payne and Oliver 2000; Nurse et al. 2006).

At 3 WAE, several herbicides provided excellent broadleaved and grass control. Seven of the PP herbicide combinations evaluated provided greater than 70% control of all broadleaved species, and of those, three herbicide combinations provided over 81% control of all grass weed species (Table 2). The two most efficacious herbicide combinations were tank-mixes of: 1) glyphosate (900 g ae ha⁻¹) plus chlorimuron (9 g ai ha⁻¹) plus imazethapyr (75 g ai ha⁻¹), and 2) glyphosate (900 g ae ha⁻¹) plus imazethapyr (77 g ai ha⁻¹) plus metribuzin (413 g ai ha⁻¹) plus flumioxazin (96 g ai ha⁻¹). Both of these mixtures provided >80% control of all the weeds evaluated in this study. In other studies, Stewart et al. (2011) reported 4 to 47% control of velvetleaf, 17 to 27% control of common ragweed, 47 to 62% control of redroot pigweed and 37-49% control of foxtail with PRE herbicides including imazethapyr, s-metolachlor/benoxacor plus metribuzin and flumetsulam/s-metolachlor followed by glyphosate.

Density and Dry Weight

At 3 WAE, several PRE herbicides reduced weed density and biomass of both broadleaved and grass weed species (Table 3 and 4). The weed density and biomass values closely reflected the weed control assessments at 3 WAE (Table 2). Based on weed density and dry weight, the two most efficacious soil-applied herbicides for the six weeds evaluated in this study were tank-mixes of glyphosate (900 g ae ha⁻¹) plus chlorimuron (9 g ai ha⁻¹) plus imazethapyr (75 g ai ha⁻¹), and glyphosate (900 g ae ha⁻¹) plus imazethapyr (77 g ai ha⁻¹) plus metribuzin (413 g ai ha⁻¹) plus flumioxazin (96 g ai ha⁻¹).

The most difficult weed to control in this study was common ragweed. Several studies have demonstrated similar findings where the early season control of common ragweed was 57% to 68%, while in contrast the control of common lambsquarters and redroot pigweed was 80% to 88% and 82% to 93%, respectively (Soltani et al. 2012, 2014; Stewart et al. 2011).

At 4 weeks after the POST application of glyphosate (900 g ae ha⁻¹), broadleaved and grass control was 91 to 100 and 78 to 97%, respectively (Table 5). The PP application of saflufenacil (25 g ai ha⁻¹), imazethapyr/saflufenacil (100 g ai ha⁻¹), imazethapyr (75 g ai ha⁻¹) plus metribuzin (425 g ai ha⁻¹), chlorimuron (9 g ai ha⁻¹), chlorimuron (9 g ai ha⁻¹) plus metribuzin (412 g ai ha⁻¹), chlorimuron (9 g ai ha⁻¹) plus imazethapyr (75 g ai ha⁻¹), or metribuzin (413 g ai ha⁻¹) plus imazethapyr (77 g ai ha⁻¹) plus flumioxazin (96 g ai ha⁻¹) followed by glyphosate (900 g ae ha⁻¹) applied POST all provided greater than 95% control of the broadleaved weeds evaluated in this study. The PP herbicide that provided the lowest numeric control of velvetleaf was 2,4-D (500 g ae ha⁻¹), of redroot pigweed was dicamba (600 g ae ha⁻¹), of common ragweed was pyroxasulfone (100 g ai ha⁻¹) plus sulfentrazone (100 g ai ha⁻¹), and of lambsquarters was

dicamba (300 g ae ha⁻¹) plus dimethenamid-p (544 g ai ha⁻¹). All of the two-pass weed control programs provided greater than 90% control of barnyard grass and green foxtail with the exception of saflufenacil (25 g ai ha⁻¹) and dicamba (600 g ae ha⁻¹). Glyphosate is a broad spectrum herbicide, and its use following a PP herbicide resulted in excellent control of all the weed species evaluated in this study, which is consistent with other studies (Soltani et al. 2012; OMAFRA, 2016b).

At 8 weeks after the POST application of glyphosate (900 g ae ha⁻¹), broadleaved and grass control was 86 to 100 and 88 to 99%, respectively (Table 6). The PP application of saflufenacil (25 g ai ha⁻¹), imazethapyr/saflufenacil (100 g ai ha⁻¹), imazethapyr (75 g ai ha⁻¹) plus metribuzin (425 g ai ha⁻¹), chlorimuron (9 g ai ha⁻¹), chlorimuron (9 g ai ha⁻¹) plus metribuzin (412 g ai ha⁻¹), chlorimuron (9 g ai ha⁻¹) plus imazethapyr (75 g ai ha⁻¹), or metribuzin (413 g ai ha⁻¹) plus imazethapyr (77 g ai ha⁻¹) plus flumioxazin (96 g ai ha⁻¹) followed by glyphosate (900 g ae ha⁻¹) applied POST all provided greater than 95% control of the broadleaved weeds evaluated in this study. The PP herbicide that provided the lowest numeric control of velvetleaf was 2,4-D (500 g ae ha⁻¹), of redroot pigweed was dicamba (600 g ae ha⁻¹), of common ragweed was pyroxasulfone (100 g ai ha⁻¹) plus sulfentrazone (100 g ai ha⁻¹), and of lambsquarters was dimethenamid-p (544 g ai ha⁻¹) plus dicamba (300 g ae ha⁻¹). All of the two-pass weed control programs provided greater than 90% control of barnyard grass and green foxtail with the exception of chlorimuron (9 g ai ha⁻¹) plus metribuzin (412 g ai ha⁻¹) and dicamba (600 g ae ha⁻¹), dimethenamid-p (544 g ai ha⁻¹) plus dicamba (300 g ae ha⁻¹), s-metolachlor/metribuzin (1443 g ai ha⁻¹) and pyroxasulfone/flumioxazin (160 g ai ha⁻¹). It is important to note, however, that differences in weed control amongst herbicide programs were still measurable. At 8 WAA, treatments consisting of glyphosate (900 g ae ha⁻¹) plus chlorimuron (9 g ai ha⁻¹) plus and

imazethapyr (75 g ai ha⁻¹) and glyphosate (900 g ae ha⁻¹) plus imazethapyr (77 g ai ha⁻¹) plus metribuzin (413 g ai ha⁻¹) plus flumioxazin (96 g ai ha⁻¹) provided up to 8, 9, 11, and 5% greater control of velvetleaf, redroot pigweed, common ragweed, and common lambsquarters, respectively, compared to other treatments evaluated. The differences in weed control amongst grass weed species were less apparent where the greatest difference among herbicide programs evaluated of barnyard grass was 3% and green foxtail was 7%.

Soybean Yield

Where weeds were controlled using dicamba (600 g ae ha⁻¹) or dicamba (300 g ae ha⁻¹) plus dimethenamid-p (544 g ai ha⁻¹), soybean yields increased over 139% compared to the weedy control (Table 7). Several weed control programs resulted in soybean yield that was similar to the weed free control; these included imazethapyr/saflufenacil (100 g ai ha⁻¹), imazethapyr (75 g ai ha⁻¹) plus metribuzin (425 g ai ha⁻¹), chlorimuron (9 g ai ha⁻¹), chlorimuron (9 g ai ha⁻¹) plus imazethapyr (75 g ai ha⁻¹), dimethenamid-p (544 g ai ha⁻¹) plus dicamba (300 g ae ha⁻¹), or metribuzin (413 g ai ha⁻¹) plus imazethapyr (77 g ai ha⁻¹) plus flumioxazin (96 g ai ha⁻¹) followed by glyphosate (900 g ae ha⁻¹) applied POST. In other studies, Soltani et al. (2014) found lower yield than untreated control with two pass application of glyphosate with chlorimuron or pyroxasulfone/flumioxazin PRE followed by glyphosate POST in conventional glyphosate-resistant soybean. Nurse et al. (2006) also found that corn yield increased when a PRE herbicide (flufenacet plus metribuzin) was followed by glyphosate compared to glyphosate alone.

The soybean yields across the evaluated two-pass weed control programs varied from 86 to 97% of the weed-free control. While some herbicide programs resulted in similar soybean seed yields to the weed free control, it will be important for farmers to choose a herbicide program

that will result in the highest profitability, considering the costs of the herbicide program and weed interference on soybean seed yield. For example, while reduced weed interference with chlorimuron (9 g ai ha⁻¹) resulted in soybean yield that was similar to the weed free control, it still yielded 14% less or a decrease of 301 kg ha⁻¹. If averaged across the average provincial soybean price in October of 2014 and 2015, the difference in yield between the weed free control and the treatment consisting of chlorimuron (9 g ai ha⁻¹) would result in \$128.57 ha⁻¹ in lost revenue (Grain Farmers of Ontario, 2016).

Profit Analysis

Net revenue among the herbicide programs evaluated varied by \$180.13 ha⁻¹ (Table 7). The following two pass-programs resulted in the greatest and similar net returns: glyphosate plus imazethapyr/saflufenacil (100 g ai ha⁻¹), imazethapyr (75 g ai ha⁻¹) plus metribuzin (425 g ai ha⁻¹), chlorimuron (9 g ai ha⁻¹), chlorimuron (9 g ai ha⁻¹) plus metribuzin (412 g ai ha⁻¹), chlorimuron (9 g ai ha⁻¹) plus imazethapyr (75 g ai ha⁻¹), dicamba (600 g ae ha⁻¹) or 2,4-D (500 g ae ha⁻¹) applied PRE followed by glyphosate (900 g ae ha⁻¹) applied POST. The least profitable two-pass herbicide program was the PP application of glyphosate (900 g ae ha⁻¹) plus s-metolachlor/metribuzin (1443 g ai ha⁻¹) followed by glyphosate (900 g ae ha⁻¹) applied POST. In other studies, Soltani et al. (2014) reported that applying PRE herbicides such as atrazine plus dicamba alone, atrazine followed by glyphosate, atrazine plus metolachlor followed by glyphosate and atrazine plus isoxaflutole followed by glyphosate POST had comparable EI to applying glyphosate twice. Because of the low cost of glyphosate, sequential applications of glyphosate applied alone have been an attractive herbicide program for many years. While it may

provide farmers with a simple and cost effective herbicide program in the short term, it will greatly increase the risk of selection for GR weed biotypes and should be avoided.

Environmental Impact

The EI values of the herbicide programs evaluated ranged from 27.5 to 43.4 (Table 7), which would be classified as medium to high risk (Stewart et al. 2011; Beckie et al. 2014). While the EI for all treatments appear to be quite high, much of the EI for each treatment can be accounted for by the sequential applications of glyphosate. This doesn't mean that the EI values should be dismissed. If a weed management practitioner planned to use a sequential application of glyphosate, there wouldn't be a substantial increase in EI if chlorimuron (9 g ai ha^{-1}) and metribuzin (412 g ai ha^{-1}) or chlorimuron (9 g ai ha^{-1}) and imazethapyr (75 g ai ha^{-1}) were added to the weed management program. By doing so, there would be a modest increase in net revenue, a significant improvement in weed control, a reduction in the selection of GR weed biotypes, and a slight increase in EI.

In conclusion, there are several herbicide options available that provide excellent control of a wide range of broadleaved and grass weed species in no-till dicamba-resistant soybean. Weed management programs that provided excellent early season weed control generally resulted in the highest soybean yield. Despite having the highest soybean yield, these herbicide programs did not always result in the highest net returns due to the cost of the herbicides. The weed control programs that provided the greatest control also had the highest EI. It is attractive for producers to choose herbicide programs that provide higher net returns and are simple to manage, such as sequential applications of glyphosate, but weed management practitioners must be aware of the risks of utilizing only one mode of action. The use of multiple modes of action is recommended

to reduce the selection intensity for HR weeds. Dicamba provided early season suppression of many broadleaved weeds and was similar to current industry standards in respect to soybean yield and net revenue. As GR weeds spread across Ontario, dicamba-resistant soybean and the concomitant use of dicamba will be a valuable weed management tool in the future.

References

- Beckie, H.J., Harker, K.N., Hall, L.M., Warwick, S.I., Légère, A., Sikkema, P.H., Clayton, G.W., Thomas, A.G., Leeson, J.Y., Séguin-Swartz, G., and Simard, M.-J. 2006. A decade of herbicide-resistant crops in Canada. *Can. J. Plant Sci.* **86**:1243-1264.
- Beckie, H.J., Sikkema, P.H. Soltani, N., Blackshaw, R.E., and Johnson E.N. 2014. Environmental impact of glyphosate-resistant weeds in Canada. *Weed Sci.* **62**:385-392.
- Brimner, T.A., Gallivan, G.J., and Stephenson, G.R. 2005. Influence of herbicide-resistant canola on the environmental impact of weed management. *Pest Manag. Sci.* **61**:47-52.
- Brookes, G., and Barfoot, P. 2015. Global income and production impacts of using GM crop technology 1996-2013. *GM Crops and Food.* **6**:13-46.
- Budd, C.M., Soltani, N., Robinson, D.E., Hooker, D.C., Miller, R.T., and Sikkema, P.H. 2016. Glyphosate-resistant horseweed (*Conyza canadensis*) dose response to saflufenacil, saflufenacil plus glyphosate, and metribuzin plus saflufenacil plus glyphosate in soybean. *Weed Sci.* **64**:727-734.
- Fausey, J.C., and Renner, K.A. 2001. Broadleaf weed control in corn (*Zea mays*) and soybean (*Glycine max*) with CGA-248757 and flumiclorac alone and in tank mixtures. *Weed Technol.* **15**:399-407.

- Fernandez-Cornejo, J. 1997. Environmental and economic consequences of technology adoption: IPM in viticulture. *Agr. Econ.* **18**:145-155.
- Gianessi, L.P. 2005. Economic and herbicide use impacts of glyphosate-resistant crops. *Pest Manag. Sci.* **61**:241-245.
- 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.
- Grain Farmers of Ontario. 2016. Historical soybean prices: July 2011 to December 2016. Online. Website: <http://www.gfo.ca/Marketing/Average-Commodity-Prices/Soybeans>
- Halford, C., Hamill, A.S., Zhang, J., and Doucet, C. 2001. Critical period of weed control in no-till soybean (*Glycine max*) and corn (*Zea mays*). *Weed Technol.* **15**:737-744.
- Johnson, B., Young, B., Matthews, J., Marquardt, P., Slack, C., Bradley, K., York, A., Culpepper, S., Hager, A., Al-Khatib, K., Steckel, L., Moechnig, M., Loux, M., Bernards, M., and Smeda, R. 2010. Weed control in dicamba-resistant soybeans. Online. *Crop Management* doi:10.1094/CM-2010-0920-01-RS.
- Knezevic, S.Z., Evans, S.P., and Mainz, M. 2003. Row spacing influences critical timing for weed removal in soybean (*Glycine max*). *Weed Technol.* **17**:666-673.
- Kovach, J., Petzoldt, C., Degnil, J., and Tette, J. 1992. A method to measure the environmental impact of pesticides. *New York's Life and Food Sciences Bulletins.* **139**:139-146.
- Eshenaur, B., Grant, J., Kovach, J., Petzoldt, C., Degni, J., and Tette, J. 2016. Environmental Impact Quotient: "A Method to Measure the Environmental Impact of Pesticides." New York State Integrated Pest Management Program, Cornell Cooperative Extension, Cornell University. 1992 – 2015. Online. Website: www.nysipm.cornell.edu/publications/EIQ

- Kulasekera, K. 2016. Estimated area, yield, production, and farm value of specified field crops, Ontario, 2012-2016. Online. Ontario Ministry of Agriculture, Food and Rural Affairs. Website: http://www.omafr.gov.on.ca/english/stats/crops/estimate_new.htm
- Mulugeta, D., and Boerboom, C.M. 2000. Critical time of weed removal in glyphosate-resistant *Glycine max*. *Weed Sci.* **48**:35-42.
- Norsworthy, J.K., McClelland, M., and Griffith, G.M. 2009. *Conyza canadensis* (L.) Cronquist response to pre-plant application of residual herbicides in cotton (*Gossypium hirsutum* L.). *Crop Protect.* **28**:62-67.
- Nurse, R.E., Swanton, C.J., Tardif, F., and Sikkema, P.H. 2006. Weed control and yield are improved when glyphosate is preceded by a residual herbicide in glyphosate-tolerant maize (*Zea mays*). *Crop Prot.* **25**:1174-1197.
- Payne, S.A., and Oliver, L.R. 2000. Weed control programs in drilled glyphosate-resistant soybean. *Weed Technol.* **14**: 413-422.
- OMAFRA - Ontario Ministry of Agriculture, Food, and Rural Affairs (2016a) Field Crop Budgets. Toronto, ON: OMAFRA Publ. 60. Online. Ontario Ministry of Agriculture, Food and Rural Affairs. Website: <http://www.omafr.gov.on.ca/english/busdev/facts/pub60.pdf>
- OMAFRA - Ontario Ministry of Agriculture, Food, and Rural Affairs (2016b) Guide to Weed Control. Toronto, ON: OMAFRA Publ. 75. 220-222.
- Soltani, N., Stewart, C.L., Nurse, R.E., Van Eerd, L.L., Vyn, R.J., and Sikkema, P.H. 2012. Weed control, environmental impact, and profitability of weed management strategies in glyphosate-resistant corn. *Am. J. Plant Sci.* **3**:1594-1607.

- Soltani, N., Nurse, R.E., and Sikkema, P.H. 2014. Two-pass weed management with preemergence and postemergence herbicides in glyphosate-resistant soybean. *Ag. Sci.* **5**:504-512.
- Spaunhorst, D.J. Siefert-Higgins, S., and Bradley, K.W. 2014. Glyphosate-resistant giant ragweed (*Ambrosia trifida*) and waterhemp (*Amaranthus rudis*) management in dicamba-resistant soybean (*Glycine max*). *Weed Technol.* **28**:131-141.
- Stewart, C.L., Nurse, R.E., Van Eerd, L.L., Vyn, R.J., and Sikkema, P.H. 2011. Weed control, environmental impact, and economics of weed management strategies in glyphosate-resistant soybean. *Weed Technol.* **25**:535-541.
- Vink, J.P., Soltani, N., Robinson, D.E., Tardif, F.J., Lawton, M.B., and Sikkema, P.H. 2012. Glyphosate-resistant giant ragweed (*Ambrosia trifida* L.) control in dicamba-tolerant soybean. *Weed Technology.* **26**:422-428.
- Yang, R.C. 2010. Towards understanding and use of mixed-model analysis of agricultural experiments. *Can. J. Plant Sci.* **90**:605-627.

Table 1. Experiment location, seeding and herbicide application dates, and soybean staging.

Environment	Year	Seeding Date	Application timing	Herbicide application Date
Ridgetown 1	2014	June 01	PP	May 20
			POST	July 02
	2015	May 08	PP	May 01
			POST	June 25
Ridgetown 2	2014	June 01	PP	May 30
			POST	July 05
	2015	May 08	PP	May 07
			POST	June 19
Woodstock	2014	June 05	PP	June 01
			POST	July 04
	2015	May 13	PP	May 06
			POST	June 16

Table 2. Percent control of velvetleaf (ABUTH), redroot pigweed (AMARE), common ragweed (AMBEL), common lambsquarters (CHEAL), common barnyardgrass (ECHCG), and green foxtail (SETVI) 3 weeks after soybean emergence in response to a preplant (PP) herbicides in no-till soybean averaged across three locations in Ridgetown and Woodstock, ON during 2014 and 2015.

Treatment ^{ab}	Rate (g ai/ae ha ⁻¹)	Visible Control (%)					
		ABUTH ^d	AMARE	AMBEL	CHEAL	ECHCG	SETVI
Control		100a	100a	100a	100a	100a	100a
Glyphosate	900	32e	47e	54e	47c	14e	15f
Saflufenacil ^c	25	79cd	79cd	58e	76b	15e	13f
Imazethapyr/saflufenacil	100	99ab	98ab	70bcde	98a	74bc	74cd
Imazethapyr	75	95abc	96abc	72bcde	97a	88bc	81bc
Metribuzin	425						
Chlorimuron	9	95abc	99ab	80bcd	98a	74bc	63d
Chlorimuron	9	93abc	99a	85b	98a	74bc	64d
Metribuzin	412						
Chlorimuron	9	99ab	100a	85bc	98a	82bc	81bc
Imazethapyr	75						
Pyroxasulfone	100	69d	85bcd	58e	94a	87bc	71cd
Sulfentrazone	100						
Dicamba	600	61de	63de	69cde	73b	46d	38e
dimethenamid-p	544	68d	71de	60e	62bc	69cd	62d
Dicamba	300						
2,4-D	500	57de	69de	62e	65bc	49d	36e
Metribuzin	413	99ab	100a	80bcd	99a	90b	87b
Imazethapyr	77						
Flumioxazin	96						

s-metolachlor/metribuzin	1443	64d	80cd	64de	65bc	85bc	68cd
Pyroxasulfone/flumioxazin	160	84bcd	93abc	70bcde	78b	85bc	69cd

Means followed by the same letter within a column are not significantly different according to Fisher's protected LSD test ($P < 0.05$).

^a All PP applications included 900 g ae ha⁻¹ of glyphosate (Roundup Weathermax 540SL formulation).

^b All treatments received a POST application of 900 g ae ha⁻¹ of glyphosate (Roundup Weathermax 540SL formulation) at the V4 soybean growth stage.

^c Merge (non-ionic surfactant) was included in the tank at 1 L ha⁻¹.

^d All data have been pooled for all locations and years. Data presented in the table have been backtransformed to the original scale.

For Review Only

Table 3. Density of velvetleaf (ABUTH), redroot pigweed (AMARE), common ragweed (AMBEL), common lambsquarters (CHEAL), common barnyardgrass (ECHCG), and green foxtail (SETVI) evaluated 3 weeks after soybean emergence (WAE) in response to a preemergence (PRE) herbicide application to no-till soybean ground averaged across three locations in Ridgetown and Woodstock, ON during 2014 and 2015.

Treatment ^{ab}	Rate (g ai/ae ha ⁻¹)	Density (no. m ⁻²)					
		ABUTH ^d	AMARE	AMBEL	CHEAL	ECHCG	SETVI
Weedy Control		12a	8abcd	35a	33ab	6ab	312a
Glyphosate	900	9ab	29a	14b	36ab	16a	209abc
Saflufenacil ^c	25	4abcde	6cde	10bc	14bc	9ab	298ab
Imazethapyr/saflufenacil	100	1e	1ef	9bc	4def	4ab	133abcde
Imazethapyr	75	2cde	1def	12b	4def	10ab	71ef
Metribuzin	425						
Chlorimuron	9	3bcde	1ef	9bc	1ef	10ab	142abcde
Chlorimuron	9	1de	0f	6c	1ef	7ab	128bcde
Metribuzin	412						
Chlorimuron	9	1de	0ef	11bc	1f	7ab	45f
Imazethapyr	75						
Pyroxasulfone	100	6abcd	7bcd	14b	4de	3b	78def
Sulfentrazone	100						
Dicamba	600	12a	27a	7bc	24ab	7ab	147abcde
dimethenamid-p	544	4abcde	28a	11bc	43a	8ab	91cdef
Dicamba	300						
2,4-D	500	8ab	20abc	13b	46a	5ab	183abcd
Metribuzin	413						
Imazethapyr	77	1e	0f	7bc	1ef	2b	62ef
Flumioxazin	96						
s-metolachlor/metribuzin	1443	6abc	22ab	10bc	33ab	4b	78def
Pyroxasulfone/flumioxazin	160	4abcde	3def	10bc	8cd	3b	47f

Means followed by the same letter within a column are not significantly different according to Fisher's protected LSD test ($P < 0.05$).

^a All PP applications included 900 g ae ha⁻¹ of glyphosate (Roundup Weathermax 540SL formulation).

^b All treatments received a POST application of 900 g ae ha⁻¹ of glyphosate (Roundup Weathermax 540SL formulation) at the V4 soybean growth stage.

^c Merge (non-ionic surfactant) was included in the tank at 1 L ha⁻¹.

^d All data have been pooled for all locations and years. Data presented in the table have been backtransformed to the original scale.

Table 4. Dry weight of velvetleaf (ABUTH), redroot pigweed (AMARE), common ragweed (AMBEL), common lambsquarters (CHEAL), common barnyardgrass (ECHCG), and green foxtail (SETVI) evaluated 3 weeks after soybean emergence (WAE) in response to a preemergence (PRE) herbicide application to no-till soybean ground averaged across three locations in Ridgeway and Woodstock, ON during 2014 and 2015.

Treatment ^{ab}	(Rate g ai/ae ha ⁻¹)	Dry Weight (g m ⁻²)					
		ABUTH ^c	AMARE	AMBEL	CHEAL	ECHCG	SETVI
Weedy Control		1.3ab	1.0cdef	11.9a	10.7a	1.3bc	41.0a
Control							
Glyphosate	900	1.4a	3.4ab	3.6bc	4.8b	5.9a	30.8ab
Saflufenacil ^d	25	0.4bcd	0.8def	2.9bcd	1.8cde	3.6ab	49.8a
Imazethapyr/saflufenacil	100	0.1cd	0.1f	3.6bc	0.7ef	1.4bc	10.1defg
Imazethapyr	75	0.2cd	0.1f	3.7bc	0.3ef	2.4abc	6.5fg
Metribuzin	425	0.3cd	0.1f	1.7bcd	0.1f	2.2bc	14.7cde
Chlorimuron	9	0.1cd	0f	1.3d	0.1f	2.0bc	15.4bcde
Chlorimuron	9	0.2cd	0.1f	2.2bcd	0f	0.9c	4.6g
Imazethapyr	75	0.9abc	1.2bcdef	4.1b	0.7ef	0.9c	10.5defg
Pyroxasulfone	100	0.7abcd	2.5abcd	3.3bcd	3.5bcd	2.2bc	14.5cde
Sulfentrazone	100	1.4a	3.6a	3.0bcd	4.0bc	2.1bc	26.7abc
Dicamba	600	0.1d	0f	2.5bcd	0.1f	0.8c	5.4fg
dimethenamid-p	544	1.2ab	1.8abcde	3.9bc	2.9bcd	1.3bc	12.2def
Dicamba	300	0.5abcd	0.3ef	3.6bc	1.2def	1.2bc	9.2efg
2,4-D	500						
Metribuzin	413						
Imazethapyr	77						
Flumioxazin	96						
s-metolachlor/metribuzin	1443						
Pyroxasulfone/flumioxazin	160						

Means followed by the same letter within a column are not significantly different according to Fisher's protected LSD test ($P < 0.05$).

^a All PP applications included 900 g ae ha⁻¹ of glyphosate (Roundup Weathermax 540SL formulation).

^b All treatments received a POST application of 900 g ae ha⁻¹ of glyphosate (Roundup Weathermax 540SL formulation) at the V4 soybean growth stage.

^c Merge (non-ionic surfactant) was included in the tank at 1 L ha⁻¹.

^d All data have been pooled for all locations and years. Data presented in the table have been backtransformed to the original scale.

Table 5. Control of velvetleaf (ABUTH), redroot pigweed (AMARE), common ragweed (AMBEL), common lambsquarters (CHEAL), common barnyardgrass (ECHCG), and green foxtail (SETVI) evaluated 4 weeks after the POST application (WAA) in response to a preplant (PP) herbicide application to no-till soybean ground followed by a POST application of glyphosate averaged across three locations in Ridgetown and Woodstock, ON during 2014 and 2015.

Treatment ^{ab}	Rate (g ai/ae ha ⁻¹)	Visible Control (%)					
		ABUTH ^d	AMARE	AMBEL	CHEAL	ECHCG	SETVI
Control		100a	100a	100a	100a	100a	100a
Glyphosate	900	91e	93de	94def	96c	84bc	85c
Saflufenacil ^c	25	96cde	96bcd	96cde	95c	93bc	88bc
Imazethapyr/saflufenacil	100	100a	99ab	96cde	99ab	94abc	94bc
Imazethapyr	75	100abc	99ab	95cde	99ab	96abc	94bc
Metribuzin	425						
Chlorimuron	9	98abcd	100a	97bcd	99ab	97ab	93bc
Chlorimuron	9	100a	100a	99b	100a	97ab	93bc
Metribuzin	412						
Chlorimuron	9	100a	100a	98bc	100a	97ab	96ab
Imazethapyr	75						
Pyroxasulfone	100	97bcde	99abc	91f	99ab	97ab	95bc
Sulfentrazone	100						
Dicamba	600	94de	89e	98bc	94c	78c	87bc
dimethenamid-p	544	94de	91de	93ef	93c	91abc	89bc
Dicamba	300						
2,4-D	500	92e	90de	95cde	94c	90bc	91bc
Metribuzin	413						
Imazethapyr	77	100ab	100a	97bcd	99ab	97ab	96ab
Flumioxazin	96						
s-metolachlor/metribuzin	1443	94de	95cde	94def	95c	97ab	94bc
Pyroxasulfone/flumioxazin	160	97bcde	99abc	94def	97bc	95abc	94bc

Means followed by the same letter within a column are not significantly different according to Fisher's protected LSD test ($P < 0.05$).

^a All PP applications included 900 g ae ha⁻¹ of glyphosate (Roundup Weathermax 540SL formulation).

^b All treatments received a POST application of 900 g ae ha⁻¹ of glyphosate (Roundup Weathermax 540SL formulation) at the V4 soybean growth stage.

^c Merge (non-ionic surfactant) was included in the tank at 1 L ha⁻¹.

^d All data have been pooled for all locations and years. Data presented in the table have been backtransformed to the original scale.

Table 6. Control of velvetleaf (ABUTH), redroot pigweed (AMARE), common ragweed (AMBEL), common lambsquarters (CHEAL), common barnyardgrass (ECHCG), and green foxtail (SETVI) evaluated 8 weeks after the POST application (WAA) in response to a preplant (PP) herbicide application to no-till soybean ground followed by a POST application of glyphosate averaged across three locations in Ridgely and Woodstock, ON during 2014 and 2015.

Treatment ^{ab}	Rate (g ai/ae ha ⁻¹)	Visible Control (%)					
		ABUTH ^d	AMARE	AMBEL	CHEAL	ECHCG	SETVI
Control		100a	100a	100a	100a	100a	100a
Glyphosate	900	95de	96de	91de	97bc	98bc	90b
Saflufenacil ^c	25	97bcde	98cd	92cde	96c	99ab	93b
Imazethapyr/saflufenacil	100	100ab	99abc	96bcd	99ab	98bc	93b
Imazethapyr	75	100ab	99ab	95bcd	99ab	98bc	95b
Metribuzin	425						
Chlorimuron	9	100ab	100a	97bc	100a	98bc	91b
Chlorimuron	9	100ab	100a	98b	100a	97bc	89b
Metribuzin	412						
Chlorimuron	9	100ab	100a	97b	100a	98bc	92b
Imazethapyr	75						
Pyroxasulfone	100	94de	98d	86e	100a	99bc	90b
Sulfentrazone	100						
Dicamba	600	96cde	91f	95bcd	96c	97bc	92b
dimethenamid-p	544	93de	92ef	89de	95c	98bc	88b
Dicamba	300						
2,4-D	500	92e	94ef	92bcde	97c	96c	93b
Metribuzin	413						
Imazethapyr	77	100abc	100a	95bcd	100a	97bc	91b
Flumioxazin	96						
s-metolachlor/metribuzin	1443	96cde	95ef	94bcd	96c	99bc	88b
Pyroxasulfone/flumioxazin	160	98abcd	98bcd	90de	97bc	99bc	89b

Means followed by the same letter within a column are not significantly different according to Fisher's protected LSD test ($P < 0.05$).

^a All PP applications included 900 g ae ha⁻¹ of glyphosate (Roundup Weathermax 540SL formulation).

^b All treatments received a POST application of 900 g ae ha⁻¹ of glyphosate (Roundup Weathermax 540SL formulation) at the V4 soybean growth stage.

^c Merge (non-ionic surfactant) was included in the tank at 1 L ha⁻¹.

^d All data have been pooled for all locations and years. Data presented in the table have been backtransformed to the original scale.

Table 7. Soybean seed yield, environmental impact (EI) and net revenue of two-pass weed management strategies used in dicamba- and glyphosate-resistant soybean averaged across three locations in Ridgely and Woodstock, ON during 2014 and 2015.

Treatment ^{ab}	Rate (g ai/ae ha ⁻¹)	Yield ^d (t ha ⁻¹)	EI	Net Revenue (\$ ha ⁻¹)
Weedy Control		0.90d		
Weed Free Control		2.51a		
Glyphosate	900	2.15bc	27.5	737.59ab
Saflufenacil ^c	25	2.05c	28.1	683.27bc
Imazethapyr/saflufenacil	100	2.19abc	29.0	718.44abc
Imazethapyr	75	2.44ab	41.1	801.61a
Metribuzin	425			
Chlorimuron	9	2.16abc	39.8	722.18ab
Chlorimuron	9	2.13bc	27.7	739.59ab
Metribuzin	412			
Chlorimuron	9	2.22abc	29.2	758.49ab
Imazethapyr	75			
Pyroxasulfone	100	2.00c	29.9	
Sulfentrazone	100			
Dicamba	600	2.15bc	43.3	716.74abc
dimethenamid-p	544	2.18abc	42.0	697.38bc
Dicamba	300			
2,4-D	500	2.05c	35.2	741.07ab
Metribuzin	413			
Imazethapyr	77	2.18abc	43.4	688.69bc
Flumioxazin	96			
s-metolachlor/metribuzin	1443	1.93c	30.8	621.48c
Pyroxasulfone/flumioxazin	160	2.08c	31.7	657.56bc

Means followed by the same letter within a column are not significantly different according to Fisher's protected LSD test ($P < 0.05$).

^a All PP applications included 900 g ae ha⁻¹ of glyphosate (Roundup Weathermax 540SL formulation).

^b All treatments received a POST application of 900 g ae ha⁻¹ of glyphosate (Roundup Weathermax 540SL formulation) at the V4 soybean growth stage.

^c Merge (non-ionic surfactant) was included in the tank at 1 L ha⁻¹.

^d All data have been pooled for all locations and years. Data presented in the table have been backtransformed to the original scale.