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Weed Control, Environmental Impact and Profitability of Weed Management Strategies in Glyphosate-Resistant Corn

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ABSTRACT

Eleven field trials were conducted over a three-year period (2006-2008) at three locations in southwestern Ontario, Canada to evaluate the effect of various weed management strategies in glyphosate-resistant corn on weed control, crop injury, corn yield, environmental impact and profit margin. No visible injury resulted from the herbicide treatments evaluated. Overall, the effect of all factors assessed were location specific. By 56 days after treatment, depending on location, glyphosate applied at the 7-8 leaf stage (LPOST), preemergence (PRE) herbicides followed by (*fb*) glyphosate LPOST and sequential glyphosate applications (EPOST (3-4 leaf stage) followed by LPOST) provided more consistent control of annual broadleaf weeds and annual grasses compared to glyphosate applied alone EPOST. Weed control at 56 days after treatment was lower when glyphosate was applied alone LPOST compared to sequential applications of glyphosate or PRE herbicides *fb* glyphosate. There were no differences in corn yield among the sequential programs evaluated; however, a yield benefit was found when a sequential program was used compared to glyphosate applied alone LPOST. Among the sequential programs the lowest environmental impact was isoxaflutole/atrazine *fb* glyphosate. The lowest profit margins were associated with atrazine, *S*-metolachlor/atrazine/benoxacor, dicamba/atrazine and glyphosate LPOST treatments compared to all other treatments. Overall, profit margins tended to be somewhat higher for treatments that included glyphosate applications. Based on these results, the most efficacious and profitable weed management program in corn was a sequential application of glyphosate; however, isoxaflutole/atrazine *fb* glyphosate was the treatment with the lowest environmental risk while also adding glyphosate stewardship benefits.

Keywords: Environmental Impact Quotient (EIQ); Glyphosate; Profit Margin; Corn; *Zea mays* L.

1. Introduction

The demand on growers to economically produce environmentally sustainable food while maintaining herbicide stewardship is increasing. To achieve this goal, data on weed control, crop yield, economics and environmental impacts of herbicides are needed to help identify the most advantageous herbicide program. Growers of glyphosate-resistant corn have several weed management options, including pre-emergence (PRE), post-emergence (POST), tankmixes and sequential applications. Traditional management strategies for corn have included atrazine [1,2]; however the future of atrazine use in corn is unclear [3,4]. Since the introduction of glyphosate resistant corn, one- or two-pass glyphosate-only applications are now options that can simplify weed management and can be an effective method used to improve weed control [2,5-7]. However, sole reliance on glyphosate increases weed selection pressure, potentially selecting for glyphosate-resistant weeds [2,8-10]. Tank-mixes or sequential applications that utilize more than one herbicide modes of action can reduce selection pressure [2].

Timing of herbicide application is also critical for effective weed control [11-14]. A single-pass herbicide program, PRE or POST can result in weed escapes if the program fails to control all weeds or has no soil residual [13,15]. Weed escapes can be more difficult to control due to increased size, resulting in reduced herbicide efficacy of rescue sprays [16,17]. Later germinating weeds are of particular concern with a single-pass application of glyphosate because of its lack of residual control [6,18]. Sequential in-crop applications of glyphosate or combining a residual PRE herbicide with a POST application

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can improve control of late-emerging weeds [5,6,18-22].

To increase sustainability, management decisions need to include an assessment of the environmental impact of weed control strategies. By using lower herbicide application rates and/or safer products, the environmental impact of weed control may be reduced. Based on toxicological and physicochemical properties of pesticides, the environmental impact quotient (EIQ) measures the relative potential risk of pesticide active ingredients on human and ecological health based on three risk components: farm worker, consumer, and environment [23,24]. A higher environmental impact (EI) indicates a greater risk of detrimental impact. The EIQ was designed to provide growers and other decision makers with one number that indicates the magnitude of relative risk of different pesticides [25-27].

Current economic pressures facing growers require that weed management programs have high efficacy while providing positive economic returns. The cost of herbicides used in a weed management program, along with their application costs, needs to be offset by profits gained from crop yields otherwise the management program is not advantageous. Economic loss can result from a failed weed management program, leading to increased weed competition and yield losses [28,29]. Weed control failure may require a rescue spray, thereby increasing costs and decreasing a grower's profit margin. Herbicide-resistant crop use is argued to provide greater economic benefits to growers compared to non-transgenic crops due to greater weed control and reduced inputs costs [30]. Yet studies by Bradley *et al.* [2], Ferrell and Witt [31] and Johnson *et al.* [29] do not indicate an increase in profitability with the use of glyphosate-resistant corn.

To justify the most appropriate weed management strategy, the decision-making process must include an assessment of herbicide efficacy, environmental impact and economic profitability, while recognizing that trade-offs among those factors will occur. Therefore, the objective of this study is to determine which herbicide strategy for glyphosate-resistant corn will be most efficacious and economically profitable while providing low environmental impact.

2. Material and Methods

2.1. Site Descriptions and Procedures

Eleven field trials were conducted in southwestern Ontario at the Greenhouse and Processing Crops Research Centre, Agriculture and Agri-Food Canada, Harrow, Ontario in 2007 and 2008, at the Huron Research Station, Exeter, Ontario in 2006, 2007 and 2008 and two different sites at the University of Guelph, Ridgetown Campus, Ridgetown, Ontario in 2006, 2007 and 2008 (RCA, Site 1 and RCB, Site 2). Soil descriptions from each location can be found in **Table 1**.

Procedures at all sites were the same unless otherwise noted. Experiments were arranged in a randomized complete block design with four replicates. There were a total of thirteen treatments: a non-treated weedy control, a weed-free control, atrazine (1000 g·ai·ha^{-1}), s-metolachlor/atrazine/benoxacor (1080 g·ai·ha^{-1}), isoxaflutole (40 g·ai·ha^{-1}) + atrazine (400 g·ai·ha^{-1}), dicamba/atrazine (1000 g·ai·ha^{-1}), glyphosate (900 g·ae·ha^{-1}; 3 - 4 leaf stage, EPOST), glyphosate (900 g·ae·ha^{-1}; 7 - 8 leaf stage, LPOST), dicamba/atrazine (1000 g·ai·ha^{-1}) followed by (*fb*) glyphosate (900 g·ae·ha^{-1}), atrazine (1000 g·ai·ha^{-1}) *fb* LPOST glyphosate (900 g·ae·ha^{-1}), s-meto-

Table 1. Soil characteristics at Harrow (2007, 2008), Exeter (2006, 2007, 2008) and Ridgetown (2006, 2007, 2008), Ontario.

Location	Year	Soil pH	Organic matter %	Soil texture	Sand	Silt %	Clay
Harrow	2007	6.0	2.6	Fox Sandy Loam	82.5	5.0	12.5
	2008	6.0	2.6	Fox Sandy Loam	82.5	5.0	12.5
Exeter	2006	7.9	3.4	Brookston Clay Loam	33.0	35.0	32.0
	2007	7.8	3.7	Brookston Clay Loam	38.0	41.0	21.0
	2008	7.9	3.0	Brookston Clay Loam	34.0	33.0	33.0
RCA	2006	6.7	5.9	Clay Loam	35.3	34.9	29.9
	2007	7.0	4.0	Sandy Clay Loam	55.3	24.2	20.5
	2008	7.4	5.0	Loam	42.9	32.8	24.4
RCB	2006	7.4	5.0	Loam	42.9	32.8	24.4
	2007	6.9	4.8	Very Fine Sandy Loam	63.1	19.3	17.6
	2008	6.8	5.3	Sandy Clay Loam	52.4	26.3	21.3

Abbreviations: RCA, Ridgetown Site 1; RCB, Ridgetown Site 2.

lachlor/atrazine/benoxacor (1080 g·ai·ha^{-1}) *fb* LPOST glyphosate (900 g·ae·ha^{-1}), isoxaflutole (40 g·ai·ha^{-1}) + atrazine (400 g·ai·ha^{-1}) *fb* LPOST glyphosate (900 g·ae·ha^{-1}), EPOST glyphosate (900 g·ae·ha^{-1}) *fb* LPOST glyphosate (900 g·ae·ha^{-1}).

Each treatment plot was 3 m (4 corn rows) wide by 8 m long at Harrow, 3 m by 10 m at Exeter and 2 m by 8 m at both sites in Ridgetown. Glyphosate-resistant corn hybrids [Pioneer 36W68; 2008, Pioneer 36W69 (Harrow); 2006, Pioneer 38H65; 2007, Pioneer 38B86; 2008, Pioneer 38M68 (Exeter); 2006, Pioneer 38H69; 2007, Pioneer 38W69; 2008, Pioneer 35F44 (Ridgetown)] were seeded at a density of at least 71,000 seeds·ha^{-1} in rows spaced 75 cm apart. Herbicides were applied using a CO_2- pressurized sprayer calibrated to deliver 222 L·ha^{-1} aqueous solution at 210 kPa using flat fan 110-03 XR nozzles (TeeJet® flat fan 11003 XR nozzles, Spraying Systems Company, P.O. Box 7900 Wheaton, IL 60189-7900) in 2007 and ULD 120-02 nozzles (VeeJet® Ultra low-drift 12002 nozzles, Spraying Systems Company, P.O. Box 7900 Wheaton, IL 60189-7900) in 2008 spaced 50 cm apart at Harrow, 200 L·ha^{-1} aqueous solution at 241 kPa using flat fan 8002 VS nozzles (TeeJet® flat fan 8002 VS nozzles, Spraying Systems Company, P.O. Box 7900 Wheaton, IL 60189-7900) in 2006 and 2007 and ULD 120-02 nozzles (2008) spaced 50 cm apart at Exeter and 200 L·ha^{-1} aqueous solution at 207 kPa using ULD 120-02 nozzles spaced 50 cm apart at Ridgetown.

Crop injury was estimated visually 7, 14 and 28 days after treatment (DAT), using a scale of 0 to 100% where a rating of 0 was defined as no visible plant injury and a rating of 100 was defined as plant death. Percent weed control was visually assessed 28 and 56 DAT using a scale of 0% to 100% where a rating of 0 was defined as no visible weed control and a rating of 100 was defined as complete control. Only data from 56 DAT are presented in this manuscript. Corn was mechanically harvested at physiological maturity using a plot combine at all sites. Corn yields were adjusted to a 15.5% moisture level.

2.2. Statistical Analyses

All data were subjected to analysis of variance and analyzed using the PROC MIXED procedure in SAS statistical software (Version 8. SAS Institute, Inc., Box 8000, SAS Circle, Cary, NC 27512). Variances were partitioned into the fixed effect of herbicide treatment and into the random effects of environment (year and location). When there was no significant interaction between environment and treatment the data were pooled. Contrast comparisons among herbicide application timings represent *a priori* orthoganol contrasts. The assumptions of the variance analysis were tested by ensuring that the residuals were random, homogeneous, with a normal distribution about a mean of zero using residual plots and a Shapiro-Wilk normality test. All percentage data required an arcsine square root transformation. Yield data did not require transformation. All percentage data presented in tables are on the back-transformed scale. Treatment means were separated at the 5% level of significance using a Fisher's Protected LSD test.

2.3. Environmental Impact

The environmental risk for each herbicide treatment was determined using published EIQ values for all active ingredients (a.i.) [24]. However, the EIQ for atrazine, metolachlor, and isoxaflutole were recalculated based on PRE vs POST application, where the plant surface persistence value (P) of 1 was used instead of 3, respectively. The environmental impact of each treatment was calculated by multiplying herbicide EIQ by the amount applied in kg·ai/ae·ha^{-1}. For herbicide products and/or tank mixes that contain more than one a.i., the EI was calculated by summing EIQs at the appropriate proportion.

2.4. Profitability Analysis

The profitability analysis is based on the level of profit margins over weed control costs, measured as gross income less herbicide and application costs. Gross income for each replication was calculated as the yield multiplied by average price for corn between 2006 and 2008, based on the claim prices reported by Agricorp (Agricorp, 1 Stone Road West, Box 3660 Station Central, Guelph, ON N1H 8M4, Canada). Herbicide costs for each treatment are based on the 2007 herbicide prices reported by AGRIS (AGRIS Co-operative Ltd., 835 Park Avenue West, Chatham, ON N7M 5J6, Canada). Application costs are determined based on cost of production data reported by the Ontario Ministry of Agriculture, Food and Rural Affairs (Field Crop Budgets, Publication 60, updated annually; Ontario Ministry of Agriculture, Food and Rural Affairs, 1 Stone Road West, Guelph, ON N1G 4Y2, Canada). All other costs of production are assumed to be constant across treatments, thus they are not considered in the analysis. Pairwise comparisons are made between treatments using SPSS (SPSS Software, Version 16.0 SPSS Inc., 233 S. Wacher Drive, Chicago, IL 60606) to test for significant differences in average profit margins between treatments. These pairwise comparisons are made across all locations and years as well as for each location (RCA, RCB, Exeter, and Harrow) in each year. This allows for testing for overall differences in profitability between treatments as well as for testing for variations in relative profitability for specific treatments between different locations, between different years, and between different location-years. If such variations are found to exist, this would suggest that profit-maximizing weed control methods may vary under different circumstances.

3. Results and Discussion

3.1. Weed Control

The dominant weed species in this study were redroot pigweed, common ragweed, common lambsquarters and velvetleaf. Because annual grass species varied by location, all species were grouped together for analysis.

3.1.1. Redroot Pigweed

All treatments provided greater than 90% control of redroot pigweed (**Table 2**). When glyphosate was applied EPOST redroot pigweed control was reduced by 7% compared to LPOST glyphosate, a PRE herbicide *fb* glyphosate or a sequential glyphosate application. Stewart *et al.* [7] also previously demonstrated that an EPOST application of glyphosate provided 7% - 11% lower redroot pigweed control compared to a sequential application of glyphosate in corn. In contrast, a sequential application of glyphosate did not improve redroot pigweed control in comparison to a single EPOST application in soybean [13]. Nurse et al. [6] reported a decrease of 35.9 plants m^{-2} of redroot pigweed when flufenacet + metribuzin *fb* glyphosate was applied compared to when glyphosate was applied alone in corn. The results of several other studies support that late-emerging weeds are controlled most effectively using sequential applications of glyphosate or by following a PRE herbicide with a

Table 2. Mean percent control of AMARE in response to weed management strategies 56 days after treatment at Exeter and Ridgetown, ON from 2006 to 2008 and Harrow, ON from 2007 to 2008[a].

Treatment	Timing	Rate	Weed control (%)
		g·ai/ae·ha^{-1}	Pooled
Weed-free check			100a
Atrazine	PRE	1000	98a
s-metolachlor/atrazine/benoxacor	PRE	1080	90b
Isoxaflutole + atrazine	PRE+PRE	40+400	99a
Dicamba/atrazine	PRE	1000	100a
Glyphosate	EPOST	900	93b
Glyphosate	LPOST	900	100a
Dicamba/atrazine *fb* glyphosate	PRE *fb* LPOST	1000 *fb* 900	100a
Atrazine *fb* glyphosate	PRE *fb* LPOST	1000 *fb* 900	100a
s-metolachlor/atrazine/benoxacor *fb* glyphosate	PRE *fb* LPOST	1080 *fb* 900	100a
Isoxaflutole + atrazine *fb* glyphosate	PRE+PRE *fb* LPOST	40 + 400 *fb* 900	100a
Glyphosate *fb* glyphosate	EPOST *fb* LPOST	900 *fb* 900	100a
Contrasts[b]			
WF **vs** glyphosate EPOST			*
WF **vs** glyphosate LPOST			NS
Glyphosate EPOST **vs** PRE *fb* glyphosate LPOST			*
Glyphosate LPOST **vs** PRE *fb* glyphosate LPOST			NS
Glyphosate EPOST *fb* glyphosate LPOST **vs** PRE *fb* glyphosate LPOST			NS
Glyphosate EPOST **vs** glyphosate EPOST *fb* glyphosate LPOST			*
Glyphosate LPOST **vs** glyphosate EPOST *fb* glyphosate LPOST			NS
Glyphosate EPOST **vs** glyphosate LPOST			*

[a]Data were pooled by environment (location and year) when the interaction between environment and treatment was non-significant. Means are presented on the back-transformed scale. Means followed by the same letter within a column are not significantly different according to Fisher's Protected LSD ($P < 0.05$); [b]*a priori* orthogonal contrasts; * = significant ($P < 0.05$). Abbreviations: AMARE, redroot pigweed; PRE, preemergence; POST, postemergence; EPOST, early postemergence; LPOST, late postemergence; RCA, Ridgetown Site 1; RCB, Ridgetown Site 2; WF, weed-free; *fb*, followed by; NS, not significant

POST application of glyphosate [6,18,20].

3.1.2. Common Ragweed

Preemergence application of *S*-metolachlor/atrazine/benoxacor provided less than 77% control of common ragweed except at RCA in 2007 (**Table 3**). Furthermore, when applied alone, atrazine PRE had no control of common ragweed at RCA in 2006 and less than 30% control at RCB in 2006 and 2007. By 56 DAT common ragweed may have escaped the soil residual provided by atrazine, resulting in the poor control observed with *S*-metolachlor/benoxacor/atrazine or atrazine alone at these locations. Glyphosate applied LPOST had as much as 17% higher common ragweed control at Exeter in 2006 compared to when glyphosate was applied EPOST. This is most likely due to common ragweed emerging after the EPOST application. Sequential applications of glyphosate increased common ragweed control compared to glyphosate applied EPOST by 19%, 2%, 22%, and 2% at RCA, RCB, and Exeter in 2006 and RCB in 2007, respectively (**Table 3**). Sequential glyphosate application also increased common ragweed control by 21% and 5% at RCA 2006 and Exeter 2007, respectively, compared to a LPOST application of glyphosate. Generally, the appli-

Table 3. Mean percent control of AMBEL in response to several weed management strategies 56 days after treatment at Exeter and Ridgetown, ON from 2006 to 2008 and Harrow, ON, 2008[a].

Treatment	Timing	Rate	Weed Control %						
		$g·ai/ae·ha^{-1}$	2006			2007			2008
			RCA	RCB	Exeter	RCA	RCB	Exeter	Pooled
Weed-free check			100a	100a	100a	100a	100a	100a	100a
Atrazine	PRE	1000	0e	26b	100a	96e	29e	99ab	65b
s-metolachlor/atrazine/benoxacor	PRE	1080	0e	44b	74c	97d	25e	77c	51b
Isoxaflutole + atrazine	PRE+PRE	40 + 400	78d	97a	100a	99b	63d	100a	99a
Dicamba/atrazine	PRE	1000	99ab	99a	100a	99b	99ab	100a	100a
Glyphosate	EPOST	900	81d	98a	78c	99b	97c	100a	98a
Glyphosate	LPOST	900	79d	97a	95b	98c	98bc	95b	99a
Dicamba/atrazine *fb* glyphosate	PRE *fb* LPOST	1000 *fb* 900	97bc	99a	100a	99b	99ab	100a	100a
Atrazine *fb* glyphosate	PRE *fb* LPOST	1000 *fb* 900	98bc	98a	100a	99b	99ab	100a	100a
s-metolachlor/atrazine/benoxacor *fb* glyphosate	PRE *fb* LPOST	1080 *fb* 900	94c	98a	99ab	98c	99ab	97ab	99a
Isoxaflutole + atrazine *fb* glyphosate	PRE + PRE *fb* LPOST	40 + 400 *fb* 900	100a	99a	100a	99b	99ab	100a	100a
Glyphosate *fb* glyphosate	EPOST *fb* LPOST	900 *fb* 900	100a	99a	99ab	99b	99ab	100a	100a
Contrasts[b]									
WF **vs** glyphosate EPOST			*	*	*	*	*	NS	NS
WF **vs** glyphosate LPOST			*	*	*	*	*	*	NS
Glyphosate EPOST **vs** PRE *fb* glyphosate LPOST			*	*	*	*	*	NS	NS
Glyphosate LPOST **vs** PRE *fb* glyphosate LPOST			*	NS	*	*	NS	*	NS
Glyphosate EPOST *fb* glyphosate LPOST **vs** PRE *fb* glyphosate LPOST			NS	NS	NS	NS	NS	NS	NS
Glyphosate EPOST **vs** glyphosate EPOST *fb* glyphosate LPOST			*	*	*	NS	*	NS	NS
Glyphosate LPOST **vs** glyphosate EPOST *fb* glyphosate LPOST			*	NS	NS	NS	NS	*	NS
Glyphosate EPOST **vs** glyphosate LPOST			NS	*	*	NS	*	*	NS

[a]Data were pooled by environment (location and year) when the interaction between environment and treatment was non-significant. Means are presented on the back-transformed scale. Means followed by the same letter within a column are not significantly different according to Fisher's Protected LSD ($P < 0.05$); [b]*a priori* orthogonal contrasts. * = significant ($P < 0.05$). Abbreviations: AMBEL, common ragweed, PRE, preemergence; POST, postemergence; EPOST, early postemergence; LPOST, late postemergence; RCA, Ridgetown Site 1; RCB, Ridgetown Site 2; WF, weed-free; *fb*, followed by; NS, not significant.

cation of a PRE herbicide *fb* glyphosate improved common ragweed control compared to a one-pass application of glyphosate applied EPOST or LPOST, but not a sequential application of glyphosate. This is supported by Nurse *et al.* [6] who found that common ragweed control was improved with a sequential application of flufenacet + metribuzin *fb* glyphosate in comparison to a single application of glyphosate in corn.

3.1.3. Common Lambsquarters

Glyphosate applied EPOST had lower common lambsquarters control compared to a PRE herbicide *fb* glyphosate in 2006 at Exeter and RCA, in 2007 at all locations and in 2008 within Environment 1 (**Table 4**). Similarly, glyphosate applied LPOST had lower common lambsquarters control compared to a PRE herbicide *fb* glyphosate in 2006 at Exeter and RCA, in 2007 at Exeter

Table 4. Mean percent control of CHEAL in response to several weed management strategies 56 days after treatment at Exeter and Ridgetown, ON from 2006 to 2008 and Harrow, ON from 2007 to 2008[a].

Treatment	Timing	Rate	Weed Control %								
		g·ai/ae·ha^{-1}	2006			2007				2008	
			Exeter	RCA	RCB	Exeter	Harrow	RCA	RCB	Env1	Env2
Weed-free check			100.0a	100.0a	100.0a	100.0a	100.0a	100.0a	100.0a	100a	100a
Atrazine	PRE	1000	99.7ab	90.4b	92.7d	98.7b	99.4a	95.4cd	89.3d	100a	95c
s-metolachlor/atrazine/benoxacor	PRE	1080	93.4cd	71.4c	91.3d	91.5c	78.2b	76.4e	79.3e	98a	46d
Isoxaflutole + atrazine	PRE + PRE	40 + 400	99.7ab	99.0a	97.5bc	100.0a	98.1a	96.8c	76.6e	100a	97bc
Dicamba/atrazine	PRE	1000	99.7ab	70.8c	97.0c	100.0a	100.0a	98.6b	99.0b	96b	100a
Glyphosate	EPOST	900	77.4e	70.8c	97.3bc	91.4c	87.6b	94.8d	95.8c	97b	98ab
Glyphosate	LPOST	900	89.0d	78.1bc	97.5bc	91.4c	100.0a	96.8c	98.8b	100a	99a
Dicamba/atrazine *fb* glyphosate	PRE *fb* LPOST	1000 *fb* 900	100.0a	100.0a	98.8b	100.0a	100.0a	99.0b	99.0b	100a	100a
Atrazine *fb* glyphosate	PRE *fb* LPOST	1000 *fb* 900	99.8ab	99.7a	97.8bc	100.0a	100.0a	98.5b	99.0b	99a	100a
s-metolachlor/atrazine/benoxacor *fb* glyphosate	PRE *fb* LPOST	1080 *fb* 900	100.0a	99.4a	97.8bc	100.0a	100.0a	98.5b	98.5b	100a	100a
Isoxaflutole + atrazine *fb* glyphosate	PRE + PRE *fb* LPOST	40 + 400 *fb* 900	100.0a	99.9a	98.5bc	100.0a	100.0a	99.0b	99.0b	100a	100a
Glyphosate *fb* glyphosate	EPOST *fb* LPOST	900 *fb* 900	97.2bc	99.0a	97.8bc	100.0a	100.0a	98.4b	98.8b	100a	99a
<u>**Contrasts**</u>[b]											
WF **vs** glyphosate EPOST			*	*	*	*	*	*	*	*	NS
WF **vs** glyphosate LPOST			*	*	*	*	NS	*	*	*	NS
Glyphosate EPOST **vs** PRE *fb* glyphosate LPOST			*	*	NS	*	*	*	*	*	NS
Glyphosate LPOST **vs** PRE *fb* glyphosate LPOST			*	*	NS	*	NS	*	NS	*	NS
Glyphosate EPOST *fb* glyphosate LPOST **vs** PRE *fb* glyphosate LPOST			*	NS	NS	NS	NS	NS	NS	NS	NS
Glyphosate EPOST **vs** glyphosate EPOST *fb* glyphosate LPOST			*	*	NS	*	*	*	*	*	NS
Glyphosate LPOST **vs** glyphosate EPOST *fb* glyphosate LPOST			*	*	NS	*	NS	*	NS	*	NS
Glyphosate EPOST **vs** glyphosate LPOST			*	NS	NS	NS	*	*	*	NS	NS

[a]Data were pooled by environment (location and year) when the interaction between environment and treatment was non-significant. Means are presented on the back-transformed scale. Means followed by the same letter within a column are not significantly different according to Fisher's Protected LSD ($P < 0.05$); [b]*a priori* orthogonal contrasts; * = significant ($P < 0.05$); Abbreviations: CHEAL, common lambsquarters, PRE, preemergence; POST, postemergence; EPOST, early postemergence; LPOST, late postemergence; RCA, Ridgetown Site 1; RCB, Ridgetown Site 2; WF, weed-free; *fb*, followed by; Env1 = Exeter and Harrow 2008; Env2 = RCA and RCB 2008; NS, not significant.

and RCA and in 2008 within Environment 1. Delaying glyphosate application improved common lambsquarters control by 12%, 12%, 2% and 3% at Exeter in 2006 and Harrow, RCA and RCB in 2007, respectively, compared to glyphosate applied EPOST (**Table 4**). A PRE herbicide *fb* glyphosate only had higher common lambsquarters control compared to a sequential glyphosate application at Exeter in 2006, otherwise the two programs did not differ. Generally, sequential glyphosate application increased control by 3% - 28% and 2% - 21% compared to glyphosate applied alone EPOST or LPOST, respectively, depending on location. The benefits of sequential glyphosate applications on common lambsquarters have been previously reported in both corn and soybean where control was between 5% - 9% and 4% - 9% higher compared to a single application of glyphosate [7,20]. This makes sense because sequential in-crop applications of glyphosate offer a grower an opportunity to control weeds escaping an EPOST glyphosate application while late emerging weeds may have been too large at the time of application to be completely controlled by a LPOST glyphosate application [5,16,18]. However, under certain environmental conditions, a single application of glyphosate has been shown to provide adequate season long control of common lambsquarters eliminating the need for a sequential application [13].

3.1.4. Velvetleaf

Preemergence herbicides applied alone provided less than 75% control of velvetleaf within Environment 1 (**Table 5**). As expected, this is largely due to the inadequate control of velvetleaf with atrazine alone or *S*-me-

Table 5. Mean percent control of ABUTH in response to several weed management strategies 56 days after treatment at Ridgetown, ON from 2006 to 2008[a].

Treatment	Timing	Rate	Weed Control (%)	
		g·ai/ae·ha^{-1}	Env1	Env2
Weed-free check			100a	100a
Atrazine	PRE	1000	1d	1c
s-metolachlor/atrazine/benoxacor	PRE	1080	1d	1c
Isoxaflutole + atrazine	PRE + PRE	40 + 400	74b	96b
Dicamba/atrazine	PRE	1000	71b	99a
Glyphosate	EPOST	900	38c	93b
Glyphosate	LPOST	900	98a	99ab
Dicamba/atrazine *fb* glyphosate	PRE *fb* LPOST	1000 *fb* 900	70b	99ab
Atrazine *fb* glyphosate	PRE *fb* LPOST	1000 *fb* 900	99a	99ab
s-metolachlor/atrazine/benoxacor *fb* glyphosate	PRE *fb* LPOST	1080 *fb* 900	99a	100a
Isoxaflutole + atrazine *fb* glyphosate	PRE + PRE *fb* LPOST	40 + 400 *fb* 900	99a	100a
Glyphosate *fb* glyphosate	EPOST *fb* LPOST	900 *fb* 900	98a	99ab
Contrasts[b]				
WF **vs** glyphosate EPOST			*	*
WF **vs** glyphosate LPOST			NS	NS
Glyphosate EPOST **vs** PRE *fb* glyphosate LPOST			*	NS
Glyphosate LPOST **vs** PRE *fb* glyphosate LPOST			NS	NS
Glyphosate EPOST *fb* glyphosate LPOST **vs.** PRE *fb* glyphosate LPOST			NS	NS
Glyphosate EPOST **vs** glyphosate EPOST *fb* glyphosate LPOST			*	NS
Glyphosate LPOST **vs** glyphosate EPOST *fb* glyphosate LPOST			NS	NS
Glyphosate EPOST **vs** glyphosate LPOST			*	NS

[a]Data were pooled by environment (location and year) when the interaction between environment and treatment was non-significant. Means are presented on the back-transformed scale. Means followed by the same letter within a column are not significantly different according to Fisher's Protected LSD (P < 0.05); [b]*a priori* orthogonal contrasts; * = significant (P < 0.05); Abbreviations: ABUTH, velvetleaf; PRE, preemergence; POST, postemergence; EPOST, early postemergence; LPOST, late postemergence; RCA, Ridgetown Site 1; RCB, Ridgetown Site 2; WF, weed-free; *fb*, followed by; Env1 = RCA 2006, RCB 2006, RCA; Env2 = RCA 2007 and RCA 2008; NS, not significant.

tolachlor/atrazine/benoxacor [32]; highlighted by the 1% control within both environments. Glyphosate applied EPOST within Environment 1 also provided limited control of velvetleaf (38%). Percent control was improved when glyphosate was preceded by a PRE herbicide. Sequential application of glyphosate or glyphosate applied LPOST both provided 60% better control of velvetleaf compared to a single glyphosate application EPOST in Environment1. This is supported by Gonzini *et al.* [20] who demonstrated that velvetleaf control was improved by 13% - 22% and 17% - 27% when PRE herbicides were followed by glyphosate or sequential applications of glyphosate were applied, respectively, compared to a single application of glyphosate.

3.1.5. Annual Grasses

Preemergence herbicides *fb* glyphosate provided greater control of annual grasses than glyphosate applied EPOST at Exeter and RCB in 2006, Exeter and Harrow in 2007, and Harrow, RCA and RCB in 2008; or glyphosate applied LPOST at Exeter in 2007 (**Table 6**). Residual control from the PRE herbicide in addition to a LPOST cleanup with glyphosate likely contributed to the increased annual grass control. Annual grass control was higher when PRE herbicides were followed by glyphosate compared to sequential glyphosate applications at Exeter in 2008; however this relationship was reversed at Harrow in 2007 and 2008. The only non-glyphosate treatments expected to control annual grasses were *S*-metolachlor/atrazine/benoxacor and isoxaflutole + atrazine. Comparison of these treatments to a sequential glyphosate application showed no differences at Harrow (2007, 2008) and had higher control at Exeter in 2008. Control of annual grasses increased by 11% - 70% and 6% - 9% with sequential glyphosate applications compared to glyphosate applied alone EPOST or LPOST, respectively, depending on location (**Table 6**). As suggested previously, EPOST glyphosate applications alone may result in weed escapes and LPOST glyphosate applications alone may not control larger weeds. Application of glyphosate LPOST provided 11% - 64% greater control of annual grasses compared to EPOST application; however, this response was location dependent. Gonzini *et al.* [20] found that in glyphosate-resistant soybean control of giant foxtail improved by 2% - 15% with sequential applications of glyphosate POST or PRE herbicides followed by a POST application of glyphosate compared to a single-pass application of glyphosate POST.

3.2. Crop Injury and Yield

There was no visual crop injury at 7 and 28 DAT for all treatments in this study (data not shown). At most locations, PRE herbicides *fb* glyphosate resulted in higher yields than when glyphosate was applied alone LPOST (**Table 7**). Nurse *et al.* [6] demonstrated that corn yield increased when a PRE herbicide (flufenacet + metribuzin) was *fb* glyphosate compared to glyphosate alone. They attributed this response to early season weed control. In our study, sequential applications of glyphosate also had higher corn yield by up to 1.9 $MT \cdot ha^{-1}$ compared to glyphosate applied LPOST at most locations. We attribute these higher yields to increased weed control. There was no difference in corn yield between glyphosate applied EPOST and sequential glyphosate applications; however, when glyphosate was applied EPOST yield increased by 1.7 $MT \cdot ha^{-1}$ compared to glyphosate applied LPOST at Exeter in 2007. Greater control of common ragweed contributed to higher corn yield at this location with glyphosate applied EPOST. In contrast, glyphosate applied EPOST reduced yield by 1.1 $MT \cdot ha^{-1}$ compared to glyphosate applied LPOST at RCB in 2008. Again, we attributed this to a decrease in weed control. At all other locations, there was no difference in corn yield between EPOST and LPOST glyphosate.

3.3. Environmental Impact

The type of application impacts the EIQ of a pesticide. Kovach *et al.* [23] considered that all POST herbicides have a greater risk due to plant surface persistence, which factors into the farm worker, consumer and environmental components of the EIQ calculation. The EIQ of PRE applied atrazine, metolachlor, and isoxaflutole (**Table 8**) were on average 8.8 lower than the same herbicide applied POST. With approximately an order of magnitude difference in the EIQ, it is critical to consider the type of application when evaluating the relative risk of weed control strategies.

The lowest EI of 6.0 was atrazine + isoxaflutole, due to the low application rate. In contrast, due to higher EIQ values, the highest EI of herbicide products applied alone was atrazine + dicamba at 24.6. Clearly, adding another active ingredient to the weed management strategy will increase the EI, but for all treatments other than atrazine + isoxaflutole, adding glyphosate less than doubles the EI. For atrazine + isoxaflutole the addition of glyphosate more than triples the EI.

Sequential glyphosate applications had a higher EI than all products applied alone and atrazine + isoxaflutole *fb* glyphosate. The EI of applying glyphosate twice was equivalent to applying atrazine + dicamba alone, atrazine *fb* glyphosate, atrazine + metolachlor *fb* glyphosate and atrazine + isoxaflutole *fb* glyphosate. Thus, the addition of the aforementioned PRE herbicides to

Table 6. Mean percent control of annual grasses in response to several weed management strategies 56 days after treatment at Exeter and Ridgetown, ON from 2006 to 2008 and Harrow, ON from 2007 to 2008[a].

Treatment	Timing	Rate $g \cdot ai/ae \cdot ha^{-1}$	Weed Control %									
			2006		2007				2008			
			Exeter	RCB	Exeter	Harrow	RCA	RCB	Exeter	Harrow	RCA	RCB
Weed-free check			100a	100a	100a	100a	100a	100a	100a	100a	100a	100a
Atrazine	PRE	1000	0d	72.9f	0e	0d	65.4d	0d	40e	1d	1f	78d
s-metolachlor/atrazine/ benoxacor	PRE	1080	71.1b	91.4de	60.1d	6.1d	95.6b	0.8b	99ab	30c	55e	81d
Isoxaflutole + atrazine	PRE + PRE	40 + 400	97.4a	93.1cde	95.5abc	76.6b	95.8b	0b	99ab	1d	96bc	94c
Dicamba/atrazine	PRE	1000	0d	68.9f	0e	2.8d	82.1c	11.0d	1f	2d	1f	1e
Glyphosate	EPOST	900	48.9bc	87.0e	84.0c	45.0c	97.0b	97.3bc	98abc	30c	75d	98b
Glyphosate	LPOST	900	98.1a	98.1abc	90.6c	100a	98.8ab	99.0ab	94cd	94b	99ab	99ab
Dicamba/atrazine *fb* glyphosate	PRE *fb* LPOST	1000 *fb* 900	39.9c	97.6bcd	91.7bc	71.4b	98.3b	93.8c	95bcd	45c	92c	99ab
Atrazine *fb* glyphosate	PRE *fb* LPOST	1000 *fb* 900	99.7a	97.8bc	100a	80.2b	98.8ab	98.8abc	92d	93b	99ab	100a
s-metolachlor/atrazine/ benoxacor *fb* glyphosate	PRE *fb* LPOST	1080 *fb* 900	99.0a	98.1abc	100a	95.6a	98.8ab	98.5abc	100a	100a	99ab	100a
Isoxaflutole + atrazine *fb* glyphosate	PRE + PRE *fb* LPOST	40 + 400 *fb* 900	100a	98.8ab	100a	96.8a	98.8ab	98.0abc	100a	93b	99ab	100a
Glyphosate *fb* glyphosate	EPOST *fb* LPOST	900 *fb* 900	98.0a	97.8bc	99.8ab	100a	98.6b	98.8abc	92d	100a	98ab	99ab
Contrasts[b]												
WF **vs** glyphosate EPOST			*	*	*	*	*	*	NS	*	*	*
WF **vs** glyphosate LPOST			NS	NS	*	NS	NS	NS	*	*	NS	NS
Glyphosate EPOST **vs** PRE *fb* glyphosate LPOST			*	*	*	*	NS	NS	NS	*	*	*
Glyphosate LPOST **vs** PRE *fb* glyphosate LPOST			NS	NS	*	*	NS	NS	NS	NS	NS	NS
Glyphosate EPOST *fb* glyphosate LPOST **vs** PRE *fb* glyphosate LPOST			NS	NS	NS	*	NS	NS	*	*	NS	NS
Glyphosate EPOST **vs** glyphosate EPOST *fb* glyphosate LPOST			*	*	*	*	NS	NS	*	*	*	NS
Glyphosate LPOST **vs** glyphosate EPOST *fb* glyphosate LPOST			NS	NS	*	NS	NS	NS	NS	*	NS	NS
Glyphosate EPOST **vs** glyphosate LPOST			*	*	NS	*	NS	NS	NS	*	*	NS

[a]Data were pooled by environment (location and year) when the interaction between environment and treatment was non-significant. Means are presented on the back-transformed scale. Means followed by the same letter within a column are not significantly different according to Fisher's Protected LSD ($P < 0.05$). [b]*a priori* orthogonal contrasts. * = significant ($P < 0.05$); Abbreviations: PRE, preemergence; POST, postemergence; EPOST, early postemergence; LPOST, late postemergence; WF, weed-free; *fb*, followed by; RCA, Ridgetown Site 1; RCB, Ridgetown Site 2; NS, not significant.

Table 7. Mean corn yield in response to several weed management strategies at Exeter and Ridgetown, ON from 2006 to 2008 and Harrow, ON from 2007 to 2008[a].

Treatment	Yield MT·ha^{-1}										
	2006			2007				2008			
	RCA	RCB	Exeter	RCA	RCB	Exeter	Harrow	RCA	RCB	Exeter	Harrow
Weedy check	2.0d	1.4d	7.1c	5.0d	0.7f	5.0e	5.0d	3.7e	8.5d	6.6b	6.3d
Weed-free check	12.8a	10.0a	11.8ab	12.7a	12.0a	11.0ab	12.6a	11.2a	15.0a	12.4a	16.7ab
Atrazine	8.4b	4.2c	11.0ab	9.5c	4.5d	10.0bcd	10.1c	8.1cd	14.0ab	11.7a	12.8c
s-metolachlor/atrazine/benoxacor	5.9c	4.6c	11.0ab	9.8c	3.0e	9.7cd	10.9c	7.5d	12.1c	12.0a	15.7b
Isoxaflutole + atrazine	12.6a	8.6ab	11.8ab	12.1a	7.3c	10.8abc	12.6ab	10.6ab	13.4b	12.8a	15.6b
Dicamba/atrazine	12.6a	8.4b	11.3ab	11.2b	10.4b	10.0bcd	9.4c	9.1c	13.7b	12.9a	11.7c
Glyphosate	12.6a	8.7ab	11.3ab	11.8ab	11.7ab	11.1ab	12.6ab	10.6ab	13.8b	12.1a	15.8b
Glyphosate	12.3a	8.1b	10.7b	11.4ab	10.7b	9.4d	11.1bc	9.9bc	14.9a	11.6a	14.5b
Dicamba/atrazine *fb* glyphosate	12.6a	8.5b	12.0a	12.5ab	12.8a	10.5abcd	12.6ab	10.7ab	14.4a	11.9a	15.9b
Atrazine *fb* glyphosate	13.0a	8.7ab	11.9ab	12.0ab	11.9ab	10.5abcd	13.7a	11.1a	13.9b	12.8a	16.2ab
s-metolachlor/atrazine/benoxacor *fb* glyphosate	13.7a	9.0ab	12.1a	11.9ab	11.7ab	11.1ab	13.4a	10.1abc	13.8b	12.4a	17.6a
Isoxaflutole + atrazine *fb* glyphosate	13.6a	8.8ab	11.9ab	12.2ab	12.4a	11.3a	12.8ab	10.5ab	13.8b	12.1a	16.5ab
Glyphosate *fb* glyphosate	13.9a	9.5ab	12.2a	12.1ab	12.6a	11.2ab	13.2ab	10.7ab	13.8b	12.5a	16.1ab
$LSD_{0.05}$	2.02	1.49	1.21	1.51	1.23	1.28	2.20	1.10	1.00	3.21	1.50
Contrasts[b]											
WF **vs** glyphosate EPOST	NS	*	NS	NS	NS	NS	NS	NS	*	NS	NS
WF **vs** glyphosate LPOST	NS	*	*	NS	*	*	*	*	NS	NS	NS
Glyphosate EPOST **vs** PRE *fb* glyphosate LPOST	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Glyphosate LPOST **vs** PRE *fb* glyphosate LPOST	NS	*	*	NS	*	*	*	*	*	NS	NS
Glyphosate EPOST *fb* glyphosate LPOST **vs** PRE *fb* glyphosate LPOST	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Glyphosate EPOST **vs** glyphosate EPOST *fb* glyphosate LPOST	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Glyphosate LPOST **vs** glyphosate EPOST *fb* glyphosate LPOST	*	*	*	NS	*	*	NS	NS	*	NS	NS
Glyphosate EPOST **vs** glyphosate LPOST	NS	NS	NS	NS	NS	*	NS	NS	*	NS	NS

[a]Data were pooled by environment (location and year) when the interaction between environment and treatment was non-significant. Means are presented on the back-transformed scale.Means followed by the same letter within a column are not significantly different according to Fisher's Protected LSD ($P < 0.05$); [b]*a priori* orthogonal contrasts. * = significant ($P < 0.05$); Abbreviations: PRE, preemergence; POST, postemergence; EPOST, early postemergence; LPOST, late postemergence; WF, weed-free; *fb*, followed by; RCA, Ridgetown Site 1; RCB, Ridgetown Site 2; NS, not significant.

Table 8. Environmental impact quotient (EIQ) and environmental impact (EI) of weed management strategies used at Exeter and Ridgetown, ON from 2006 to 2008 and Harrow, ON from 2007 to 2008.

Active ingredient(s)	Timing	Individual EIQ values[a]	Product Rate g·ai/ae·ha^{-1}	EI[b]
Atrazine	PRE	13.6	1000	13.6
s-metolachlor/atrazine/benoxacor	PRE	14.2/13.6	1080	15.0
Atrazine + isoxaflutole	PRE	13.6/13.3	440	6.0
Dicamba/atrazine	PRE	22.9/28.0	1000	24.6
Glyphosate	EPOST	15.3	900	13.8
Glyphosate	LPOST		900	13.8
Dicamba/atrazine *fb* glyphosate	PRE *fb* LPOST		1000 *fb* 900	38.4
Atrazine *fb* glyphosate	PRE *fb* LPOST		1000 *fb* 900	27.4
s-metolachlor/atrazine/benoxacor *fb* glyphosate	PRE *fb* LPOST		1080 *fb* 900	28.8
Atrazine + isoxaflutole *fb* glyphosate	PRE *fb* LPOST		440 *fb* 900	19.8
Glyphosate *fb* glyphosate	EPOST *fb* LPOST		1800	27.5

[a]EIQ values for each a.i. obtained from Kovach *et al.* (1999), except for atrazine, metolachlor, and isoxaflutole which were calculated according to formula developed by Kovach *et al.* (1992) using PRE vs POST application; [b]EI values for products with more than one a.i. were obtained by summing the relative proportion of each a.i.; Abbreviations: EPOST, early postemergence; LPOST, late postemergence; *fb*, followed by; EIQ, environmental impact quotient; EI, environmental impact.

glyphosate-resistant corn production is strongly recommended based on equivalent environmental risk as well as resistance management.

3.4. Profitability Analysis

The results of the profitability analysis indicate that across all locations and years no significant differences in profit margins exist between the following treatments: isoxaflutole + atrazine, glyphosate EPOST, glyphosate LPOST, dicamba/atrazine followed by (*fb*) glyphosate, atrazine *fb* glyphosate, *S*-metolachlor/atrazine/benoxacor *fb* glyphosate, isoxaflutole + atrazine *fb* glyphosate and sequential applications of glyphosate (**Table 9**). Aside from the weedy check treatment, the lowest profit margins were found in the atrazine and *S*-metolachlor/ atrazine/benoxacor treatments. Other than the weedy check, relatively few significant differences existed between treatments within each location and within each year. At both Ridgetown locations, profit margins across all three years only were reduced for the atrazine and *S*-metolachlor/atrazine/benoxacor treatments compared to almost all other treatments. At Exeter, profit margins for the *S*-metolachlor/atrazine/benoxacor treatment were lower than the profit margins for dicamba/atrazine, glyphosate EPOST and sequential applications of glyphosate. At Harrow, only the atrazine and dicamba/atrazine treatments were significantly lower in profit margins than most of the other treatments. Similarly, other than the weedy check, there are few differences in profit margins between treatments found within each year. In 2006 and 2007, atrazine and *S*-metolachlor/atrazine/benoxacor have reduced profit margins compared to all other treatments. In addition, in 2007 isoxaflutole + atrazine had reduced profit margins compared to several other treatments (**Table 9**). In 2008, there are no differences in profit margins between any of the herbicide treatments.

Relatively little change in these results can be found when examining profit margins within each location-year (**Table 10**), as the significant differences that exist are consistent for the most part with the results discussed above. Among the 11 location-years, treatments that are found to have recurring lower profit margins compared to other treatments include the atrazine, *S*-metolachlor/ atrazine/benoxacor, dicamba/atrazine and glyphosate LPOST treatments. Overall, profit margins tend to be somewhat higher for treatments that include glyphosate applications.

4. Conclusions

In summary, PRE herbicides *fb* glyphosate LPOST and sequential glyphosate applications provided greater control of annual broadleaf weeds and annual grasses compared to single glyphosate applications. This is due to control of weed escapes through residual control of PRE herbicides and/or the control provided by a second glyphosate application LPOST. Generally, weed control with glyphosate applied LPOST was greater than weed control with glyphosate applied EPOST; however, this

Table 9. Profit margins over weed control costs by treatment for corn from 2006-2008 (Cdn$ ha^{-1}).[a]

Treatment	All locations	RCA (2006-2008)	RCB (2006-2008)	Exeter (2006-2008)	Harrow (2006-2008)	2006	2007	2008
Weedy check	757.75d	543.18c	543.99d	1114.82c	864.61d	536.91c	720.47e	960.65b
Atrazine	1412.22c	1289.26b	1125.34bc	1621.11ab	1713.65bc	1169.70b	1259.09d	1747.24a
s-metolachlor/atrazine/benoxacor	1351.99c	1131.82b	957.38c	1541.53b	1989.87ab	1049.47b	1167.81d	1763.07a
Isoxaflutole + atrazine	1708.07ab	1748.63a	1440.23ab	1674.68ab	2099.08a	1630.41a	1525.66c	1948.72a
Dicamba/atrazine	1640.18b	1630.19a	1608.95a	1731.40a	1565.19c	1599.44a	1543.63bc	1767.29a
Glyphosate EPOST	1802.30ab	1743.29a	1700.10a	1740.17a	2137.29a	1619.93a	1780.93a	1960.43a
Glyphosate LPOST	1707.24ab	1671.00a	1678.37a	1631.36ab	1918.74abc	1542.99a	1630.55abc	1907.12a
Dicamba/atrazine *fb* glyphosate	1772.99ab	1733.26a	1730.80a	1644.70ab	2088.29ab	1595.85a	1744.40abc	1934.42a
Atrazine *fb* glyphosate	1809.47a	1764.77a	1683.67a	1715.58ab	2206.08a	1637.21a	1760.95ab	1987.19a
s-metolachlor/atrazine/benoxacor *fb* glyphosate	1806.33a	1730.03a	1670.69a	1703.11ab	2279.08a	1685.68a	1734.02abc	1969.12a
Isoxaflutole + atrazine *fb* glyphosate	1782.02ab	1749.30a	1687.47a	1672.54ab	2137.15a	1648.68a	1738.68abc	1925.37a
Glyphosate *fb* glyphosate	1830.74a	1787.24a	1747.29a	1740.72a	2156.20a	1729.58a	1793.85a	1943.50a

[a]Means within columns that are followed by the same letter are not significantly different from each other (P < 0.05); Abbreviations: EPOST, early postemergence; LPOST, late postemergence; *fb*, followed by; RCA, Ridgetown Site 1; RCB, Ridgetown Site 2.

Table 10. Profit margins over weed control costs by treatment for corn, by location-year (Cdn$ ha^{-1}).[a]

Treatment	RCA 2006	RCB 2006	Exeter 2006	RCA 2007	RCB 2007	Exeter 2007	Harrow 2007	RCA 2008	RCB 2008	Exeter 2008	Harrow 2008
Weedy check	309.03d	220.85c	1080.86b	759.72d	105.20g	1257.78bc	759.17e	560.80f	1305.91c	1005.83c	970.05d
Atrazine	1246.26b	609.40b	1653.45a	1420.30c	659.38e	1451.99abc	1504.68cd	1201.23de	2107.22ab	1757.88ab	1922.61bc
s-metolachlor/ atrazine/benoxacor	853.03c	653.65b	1641.72a	1449.31bc	408.05f	1195.94c	1617.95bcd	1093.12e	1810.42b	1786.94ab	2361.78ab
Isoxaflutole + atrazine	1875.54a	1260.92a	1754.77a	1799.10a	1060.29d	1368.47abc	1874.78ab	1571.23ab	1999.48ab	1900.81ab	2323.38ab
Dicamba/atrazine	1878.06a	1241.97a	1678.30a	1664.68abc	1537.75c	1589.01ab	1383.06d	1347.83cd	2047.12ab	1926.91a	1747.31c
Glyphosate EPOST	1882.32a	1286.49a	1690.99a	1765.79a	1744.34abc	1721.71a	1891.90ab	1581.77ab	2069.48ab	1807.81ab	2382.68ab
Glyphosate LPOST	1834.39a	1191.40a	1603.19a	1707.35ab	1604.13bc	1548.89abc	1661.85bcd	1471.25abc	2239.57a	1742.00b	2175.63abc
Dicamba/atrazine *fb* glyphosate	1834.08a	1206.81a	1746.66a	1820.32a	1867.73a	1460.07abc	1829.48abc	1545.37ab	2117.86a	1727.37b	2347.10ab
Atrazine *fb* glyphosate	1910.84a	1257.12a	1743.67a	1766.26a	1736.89abc	1528.20abc	2012.45a	1617.20a	2056.99ab	1874.88ab	2399.70ab
s-metolachlor/ atrazine/benoxacor *fb* glyphosate	2005.32a	1289.86a	1761.85a	1733.03ab	1703.40abc	1546.49abc	1953.18ab	1451.72bc	2018.80ab	1800.97ab	2604.99a
Isoxaflutole + atrazine *fb* glyphosate	1978.42a	1250.31a	1717.31a	1762.15a	1795.44ab	1543.70abc	1853.42ab	1507.33abc	2016.67ab	1756.60ab	2420.88ab
Glyphosate *fb* glyphosate	2040.41a	1372.11a	1776.23a	1763.34a	1847.29a	1625.20ab	1939.57ab	1557.97ab	2022.48ab	1820.73ab	2372.83ab

[a]Means within columns that are followed by the same letter are not significantly different from each other (P < 0.05). Abbreviations: EPOST, early postemergence; LPOST, late postemergence; *fb*, followed by; RCA, Ridgetown Site 1; RCB, Ridgetown Site 2.

generally did not translate into a yield benefit and often resulted in yield losses due to prolonged early season weed competition. A yield benefit was found with both sequential herbicide programs compared to a single application of glyphosate LPOST. However, corn yield did not differ between the sequential herbicide programs and glyphosate applied EPOST.

Based on the EIQ, the sequential herbicide programs had a greater environmental impact than one-pass herbicides programs, except dicamba/atrazine alone, which was equivalent to several two-pass treatments. Isoxaflutole/atrazine *fb* glyphosate had the lowest environmental impact of the sequential herbicide programs evaluated. Overall, profit margins were moderately higher for treatments that included a glyphosate application (glyphosate alone or applied LPOST following a PRE herbicide). While glyphosate applied EPOST may appear to achieve the same management goals, the impact of reduced weed control over time could negatively affect future profit margins. Overall, these data showed that glyphosate *fb* glyphosate was the most efficacious and profitable treatment; however, for the purposes of glyphosate stewardship, and reduced environmental impact, isoxaflutole/atrazine *fb* glyphosate is also recommended as a profitable weed management system.

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REFERENCES

[1] G. R. Armel, H. P. Wilson, R. J. Richardson and T. E. Hines, "Mesotrione, Acetochlor, and Atrazine for Weed Management in Corn (*Zea mays*)," *Weed Technology*, Vol. 17, No. 2, 2003, pp. 284-290. doi:10.1614/0890-037X(2003)017[0284:MAAAFW]2.0.CO;2

[2] B. G. Young, "Changes in Herbicide Use Patterns and Production Practices Resulting from Glyphosate-Resistant Crops," *Weed Technology*, Vol. 20, No. 2, 2006, pp. 301-307. doi:10.1614/WT-04-189.1

[3] G. R. W. Nice, F. Whitford, B. Johnson and C. Janssen, "Assessing the Impact of Educating Growers about Proper Use of Atrazine in Pesticide Applicator Recertification Programs," *Weed Technology*, Vol. 22, No. 2, 2008, pp. 326-330. doi:10.1614/WT-07-146.1

[4] C. J. Swanton, R. H. Gulden and K. Chandler, "A Rationale for Atrazine Stewardship in Corn," *Weed Science*, Vol. 55, No. 1, 2007, pp. 75-81. doi:10.1614/WS-06-104.1

[5] J. W. Barnes and L. R. Oliver, "Cloransulam Antagonizes Annual Grass Control with Aryloxyphenoxypropionate Graminicides but Not Cyclohexanediones," *Weed Technology*, Vol. 18, 2004, pp. 763-772. doi:10.1614/WT-03-181R

[6] R. E. Nurse, C. J. Swanton., F. J. Tardif and P. H. Sikkema, "Weed Control and Yield Are Improved When Glyphosate Is Preceded by a Residual Herbicide in Glyphosate-Tolerant Maize (*Zea mays*)," *Crop Protection*, Vol. 25, No. 11, 2006, pp. 1174-1179. doi:10.1016/j.cropro.2006.02.015

[7] C. L. Stewart, R. E. Nurse, A. S. Hamill and P. H. Sikkema, "Precipitation Influences Pre- and Post-Emergence Herbicide Efficacy in Corn," *American Journal of Plant Science*, Vol. 3, No. 9, 2012, pp. 1193-1204. doi:10.4236/ajps.2012.39145

[8] S. O. Duke, "Taking Stock of Herbicide-Resistant Crops Ten Years after Introduction," *Pest Management Science*, Vol. 61, No. 3, 2005, pp. 211-218. doi:10.1002/ps.1024

[9] I. Heap, "The International Survey of Herbicide Resistant Weeds," 2012. http://www.weedscience.org

[10] R. E. Jones and R. W. Medd, "Economic Thresholds and the Case for Longer Term Approaches to Population Management of Weeds," *Weed Technology*, Vol. 14, No. 2, 2000, pp. 337-350. doi:10.1614/0890-037X(2000)014[0337:ETATCF]2.0.CO;2

[11] J. A. Bond and J. L. Griffin, "Weed Control in Corn (*Zea mays*) with an Imazethapyr Plus Imazapyr Prepackaged Mixture," *Weed Technology*, Vol. 19, No. 4, 2005, pp. 992-998. doi:10.1614/WT-04-267R1.1

[12] B. C. Johnson, B. G. Young and J. L. Matthews, "Effect of Postemergence Application Rate and Timing of Mesotrione on Corn (*Zea mays*) Response and Weed Control," *Weed Technology*, Vol. 16, No. 2, 2002, pp. 414-420. doi:10.1614/0890-037X(2002)016[0414:EOPARA]2.0.CO;2

[13] C. L. Stewart, R. E. Nurse, A. S. Hamill and P. H. Sikkema, "Environment and Soil Conditions Influence Pre- and Post-Emergence Herbicide Efficacy in Soybean," *Weed Technology*, Vol. 24, No. 3, 2010, pp. 234-243. doi:10.1614/WT-09-009.1

[14] C. J. Swanton, A. Shrestha, K. Chandler and W. Deen, "An Economic Assessment of Weed Control Strategies in No-Till Glyphosate-Resistant Soybean (*Glycine max*)," *Weed Technology*, Vol. 14, No. 4, 2000, pp. 755-763. doi:10.1614/0890-037X(2000)014[0755:AEAOWC]2.0.CO;2

[15] B. Hartzler, "Is One-Pass Weed Control a Realistic Goal?" Department of Agronomy, Iowa State University Extension Agronomy, 1996, 3 p.

[16] S. A. Gower, M. M. Loux, J. Cardina and S. K. Harrison, "Effect of Planting Date, Residual Herbicide, and Post-Emergence Application Timing on Weed Control and Grain Yield in Glyphosate-Tolerant Corn (*Zea mays*)," *Weed Technology*, Vol. 16, No. 3, 2002, pp. 488-494. doi:10.1614/0890-037X(2002)016[0488:EOPDRH]2.0.CO;2

[17] M. M. Loux, A. F. Dobbels, W. G. Johnson, G. R.W Nice, T. T Bauman and J. M. Stachler, "Weed Control Guide

for Ohio and Indiana," Ohio State University Extension Bulletin 789/Purdue Extension Pub No. WS16, 2008, 201 p.

[18] S. A. Payne and L. R. Oliver, "Weed Control Programs in Drilled Glyphosate-Resistant Soybean," *Weed Technology*, Vol. 14, No. 2, 2000, pp. 413-422. doi:10.1614/0890-037X(2000)014[0413:WCPIDG]2.0.CO;2

[19] J. L. Corbett, S. D. Askew, W. E. Thomas and J. W. Wilcut, "Weed Efficacy Evaluations for Bromoxynil, Glufosinate, Glyphosate, Pyrithiobac, and Sulfosate," *Weed Technology*, Vol. 18, No. 2, 2004, pp. 443-453. doi:10.1614/WT-03-139R

[20] L. C. Gonzini, S. E. Hart and L. M. Wax, "Herbicide Combinations for Weed Management in Glyphosate-Resistant Soybean (*Glycine max*)," *Weed Technology*, Vol. 13, No. 2, 1999, pp. 354-360.

[21] R. E. Nurse, A. S. Hamill, C. J. Swanton, F. J. Tardif, W. Deen and P. H. Sikkema, "Is the Application of a Residual Herbicide Required Prior to Glyphosate Application in No-Till Glyphosate-Tolerant Soybean (*Glycine max*)?" *Crop Protection*, Vol. 26, No. 4, 2007, pp. 484-489. doi:10.1016/j.cropro.2006.04.018

[22] L. E. Steckel, C. L. Sprague and A. G. Hager, "Common Waterhemp (*Amaranthus rudis*) Control in Corn (*Zea mays*) with Single Preemergence and Sequential Applications of Residual Herbicides," *Weed Technology*, Vol. 16, No. 4, 2002, pp. 755-761. doi:10.1614/0890-037X(2002)016[0755:CWARCI]2.0.CO;2

[23] J. Kovach, C. Petzoldt, J. Degni and J. Tette, "A Method to Measure the Environmental Impact of Pesticides," *New York's Food and Life Sciences Bulletins*, Vol. 139, 1992, pp. 139-146.

[24] J. Kovach, C. Petzoldt, J. Degni and J. Tette, "A Method to Measure the Environmental Impact of Pesticides," 2012. http://www.nysipm.cornell.edu/publications/eiq/

[25] J. Fernandez-Cornejo, "Environmental and Economic Consequences of Technology Adoption: IPM in Viticulture," *Agricultural Economics*, Vol. 18, No. 2, 1998, pp. 145-155. doi:10.1016/S0169-5150(97)00054-6

[26] G. Edwards-Jones and O. Howells, "The Origin and Hazard of Inputs to Crop Protection in Organic Farming Systems: Are They Sustainable?" *Agricultural Systems*, Vol. 67, 2001, pp. 31-47. doi:10.1016/S0308-521X(00)00045-7

[27] C. R. Ziegler, D. W. Donahue, F. A. Drummond and S. N. Smith, "The Ecological Economics of Insecticide Use Associated with the Maine Potato Industry Based on a Producer Survey," *American Journal of Alternative Agriculture*, Vol. 17, No. 4, 2002, pp. 159-166. doi:10.1079/AJAA2002159

[28] P. R. Bradley, W. G. Johnson, S. E. Hart, M. L. Buesinger and R. E. Massey, "Economics of Weed Management in Glufosinate-Resistant Corn (*Zea mays* L.)," *Weed Technology*, Vol. 14, No. 3, 2000, pp. 495-501. doi:10.1614/0890-037X(2000)014[0495:EOWMIG]2.0.CO;2

[29] W. G. Johnson, P. R. Bradley, S. E. Hart, M. L. Buesinger and R. E. Massey, "Efficacy and Economics of Weed Management in Glyphosate-Resistant Corn (*Zea mays*)," *Weed Technology*, Vol. 14, No. 1, 2000, pp. 57-65. doi:10.1614/0890-037X(2000)014[0057:EAEOWM]2.0.CO;2

[30] L. P. Gianessi, "Economic and Herbicide Use Impacts of Glyphosate-Resistant Crops," *Pest Management Science*, Vol. 61, No. 3, 2005, pp. 241-245. doi:10.1002/ps.1013

[31] J. A. Ferrell and W. W. Witt, "Comparison of Glyphosate with Other Herbicides for Weed Control in Corn (*Zea mays*): Efficacy and Economics," *Weed Technology*, Vol. 16, No. 4, 2002, pp. 701-706. doi:10.1614/0890-037X(2002)016[0701:COGWOH]2.0.CO;2

[32] Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA), "Guide to Weed Control, Publication 75," Toronto, 2008, 379 p.

