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Comparison of a Glyphosate-Resistant Canola (*Brassica napus* L.) System with Traditional Herbicide Regimes[1]

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Abstract: Herbicide-resistant cultivars account for over 90% of the canola grown in western Canada and cultivars resistant to glyphosate dominate the market. Field experiments were conducted at three locations in Alberta to compare the glyphosate system with more traditional herbicide regimes. Glyphosate applied before seeding in spring resulted in better weed control, lower dockage, and higher canola yield and net return than 2,4-D applied in the fall. Glyphosate applied once (two- to four-leaf canola) or twice (two- to four-leaf followed by five- to six-leaf canola) in-crop provided similar weed control, dockage, and canola yield as ethalfluralin applied PRE in the fall followed by an in-crop mixture of sethoxydim, ethametsulfuron, and clopyralid; and superior weed control and canola yield and lower dockage than ethalfluralin alone or an in-crop mixture of sethoxydim and ethametsulfuron. The in-crop glyphosate applications resulted in higher net revenues than the other treatments. There was little or no advantage to applying glyphosate twice compared with once in-crop. The amount of active ingredient entering the environment varied with the herbicide regime but was lower with the glyphosate system than with most of the traditional regimes, especially when glyphosate was applied only once in-crop.

Nomenclature: Clopyralid; 2,4-D; ethalfluralin; ethametsulfuron; glyphosate; sethoxydim; canola, *Brassica napus* L. 'LG 3235' and 'DKL 3235'.

Additional index words: Conventional canola; dockage; economics; environmental impact; GMO; herbicide-resistant canola; weed biomass.

INTRODUCTION

Over 90% of canola presently grown in western Canada is resistant to glyphosate, glufosinate, or imidazolinone herbicides, with cultivars resistant to glyphosate dominating the market. The introduction of the technology has provided growers with an effective tool to manage weeds that were difficult to control in canola (Harker et al. 2000). In addition, there have been reports that growing herbicide-resistant canola cultivars can result in higher economic returns than more traditional herbicide systems (Canola Council of Canada 2001).

Traditionally, growers have had to rely on mixtures of herbicides with different mechanisms of action for broad-spectrum weed control in canola. A common treatment was a preplant soil incorporation of a dinitroaniline herbicide, such as ethalfluralin or trifluralin (Friesen and Bowren 1973), in fall or spring. This treatment was often followed by in-crop herbicides alone or in mixture including sethoxydim, clopyralid, and ethametsulfuron for control of monocot weeds (Chow et al. 1983; Harker and O'Sullivan 1993), Canada thistle (*Cirsium arvense* L.) (O'Sullivan and Kossatz 1984), and closely related cruciferous weeds (Blackshaw 1989; Swanton and Chandler 1989), respectively. Although these herbicide mixtures were often effective, there was concern that costs may be prohibitive (Blackshaw and Harker 1992) and that the risk of herbicide-induced canola injury may increase with some of the mixtures (Harker et al. 1995). In addition, these herbicide mixtures were often ineffective for controlling weeds such as catchweed bedstraw (*Galium aparine* L.) and redstem filaree [*Erodium cicutarium* (L.) L'Her. ex Ait].

Concomitant with the introduction of herbicide-resistant canola, minimum- or zero-tillage cropping systems have been increasing in popularity in western Canada. Where spring tillage is eliminated, canola growers often apply glyphosate before seeding to reduce the competitive impact of early emerging weeds on the crop (Clayton et al. 2002). In a glyphosate-resistant canola system, there is concern that multiple glyphosate applications (pre-seed, once or twice in-crop and preharvest or post-

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[3] Letters following this symbol are a WSSA-approved computer code from *Composite List of Weeds,* Revised, 1989. Available only on computer disk from WSSA, 810 East 10th Street, Lawrence, KS 66044-8897.

harvest) could accelerate the selection of glyphosate-resistant weeds (Derksen et al. 1999; Maxwell et al. 1994). Although there is presently no evidence for this in western Canada (Beckie et al. 2001), resistance to glyphosate has been documented elsewhere (Lee and Ngim 2000; Powles et al. 1998; Pratley et al. 1999; VanGessel 2001). A previous study found that 2,4-D applied in fall compared with spring was more effective for controlling the winter annual weeds field pennycress (*Thlaspi arvense* L.) and flixweed [*Descurainia sophia* (L.) Webb ex Prantl] (Kirkland 1989). Thus, a fall application of 2,4-D could possibly provide effective winter annual control and reduce the need for a pre-seed glyphosate application in canola.

The objectives of this study were to compare the relative merits of the glyphosate-resistant canola system with more traditional herbicides applied preplant and in-crop, and to assess the effectiveness of a fall application of 2,4-D compared with a pre-seed spring application of glyphosate.

MATERIALS AND METHODS

Field Operations. A field study consisting of nine experiments was conducted under zero-tillage management systems in 2001, 2002, and 2003 at Beaverlodge (55°13′N, 119°26′W), Lacombe (52°28′N, 113°44′W), and Lethbridge (49°38′N, 112°47′W), AB, Canada. Soils at these respective locations were a Mollic Cryoboralfs clay loam, a Typic Haplustolls clay loam, and a Typic Haplustolls loam. Each experiment was conducted on a different study site, was previously seeded to a cereal crop, each year.

Natural weed populations at Lacombe and Lethbridge were supplemented by spreading seed of select species on the soil surface in the fall before seeding canola the following spring. Supplementary weeds at both locations were field pennycress (200 to 500 seeds/m^2) and volunteer barley (*Hordeum vulgare* L.) and wild oat (*Avena fatua* L.), each at 100 to 150 seeds/m^2. In addition, the natural weed population was supplemented with redstem filaree (100 seeds/m^2) and wild buckwheat (*Polygonum convolvulus* L.) (250 seeds/m^2) at Lacombe and with flixweed (3,000 seeds/m^2) and kochia [*Kochia scoparia* (L.) Schrad.] (150 seeds/m^2) at Lethbridge. No weed supplementation occurred at Beaverlodge because the naturally occurring weed infestation was relatively high. Weeds were identified before in-crop herbicide application each spring. Supplementary and naturally occurring weeds present at each location are listed in Table 1. Although the overall weed population varied among years, differences in species composition among years at each location were minor. The weed spectrum present at each location was representative of that present in fields in Alberta during a typical growing season (Leeson et al. 2001).

Table 1. Weed species present at Beaverlodge, Lacombe, and Lethbridge, AB Canada.[a]

Weed species	Beaverlodge	Lacombe	Lethbridge
Catchweed bedstraw	X	X	
Chickweed	X	X	
Common groundsel	X		
Common hempnettle		X	
Common lambsquarters	X	X	X
Dandelion	X	X	X
Field pennycress	X	X	X
Flixweed			X
Green foxtail			X
Henbit		X	
Kochia			X
Narrowleaf hawksbeard	X		
Perennial sowthistle		X	X
Pineappleweed	X		
Redroot pigweed		X	X
Redstem filaree		X	X
Roundleaved mallow			X
Russian thistle		X	X
Shepherdspurse	X	X	X
Volunteer barley	X	X	X
White clover	X		
Wild buckwheat	X	X	X
Wild mustard		X	X
Wild oat	X	X	X

Scientific names are as follows: chickweed, *Stellaria media* (L.) Cyrillo; common groundsel, *Senecio vulgaris* L.; common hempnettle, *Galeopsis tetrahit* L.; dandelion, *Taraxacum officinale* Weber in Wiggers; green foxtail, *Setaria viridis* (L.) Beauv.; henbit, *Lamium amplexicaule* L.; narrowleaf hawksbeard, *Crepis tectorum* L.; pineappleweed, *Matricaria matricarioides* Less. C. L. Porter; redroot pigweed, *Amaranthus retroflexus* L.; round-leaved mallow, *Malva rotundifolia* auc. non L.; Russian thistle, *Salsola iberica* Sennen & Pau; shepherdspurse, *Capsella bursa-pastoris* (L.) Medik; white clover, *Trifolium repena* L.

Glyphosate-resistant canola ('LG 3235' in 2001 and 2002 and 'DKL 3235' in 2003)[4] was direct seeded at 8 kg/ha in 20-cm rows. The same canola cultivar was used for the traditional herbicide regimes as well as for the glyphosate-resistant system to avoid any confounding effects of cultivar differences on canola yield and other variables. Seed drills with knife openers were used at Beaverlodge and Lacombe, whereas a double-disc press drill was used at Lethbridge. Seeding dates at all locations occurred between April 24 and May 14. Plot size was 3.7 by 20 m at Beaverlodge, 3.7 by 15.2 m at Lacombe, and 2.1 by 6.0 m at Lethbridge.

[4] Monsanto Canada Inc., 67 Scurfield Boulevard, Winnipeg, MB R3Y 1G4, Canada.

Table 2. Herbicides and herbicide rates used in the study.

Pre-seed			In-crop			
Treatment	Herbicide[a]	Rate	Treatment	Herbicide[a]	Rate	Total applied
		g ai or ae/ha			g ai or ae/ha	
1	2,4-D[b]	560	1	Glyphosate × 2[d]	450 + 450	1,460
1	2,4-D[b]	560	2	Glyphosate × 1[d]	450	1,010
1	2,4-D[b]	560	3	Ethalfluralin[b]	1, 100	1,660
1	2,4-D[b]	560	4	Ethalfluralin[b], sethoxydim + ethametsulfuron + clopyralid[e]	1, 100, 200 + 22 + 150	2,030
1	2,4-D[b]	560	5	Sethoxydim + etamethsulfuron[e]	200 + 22	782
2	Glyphosate[c]	450	1	Glyphosate × 2[d]	450 + 450	1,350
2	Glyphosate[c]	450	2	Glyphosate × 1[d]	450	900
2	Glyphosate[c]	450	3	Ethalfluralin[b]	1, 100	1,550
2	Glyphosate[c]	450	4	Ethalfluralin[b], sethoxydim + ethametsulfuron + clopyralid[e]	1, 100, 200 + 22 + 150	1,922
2	Glyphosate[c]	450	5	Sethoxydim + ethametsulfuron[e]	200 + 22	672
3	2,4-D[b] + glyphosate[c]	560 + 450	1	Glyphosate × 2[d]	450 + 450	1,910
3	2,4-D[b] + glyphosate[c]	560 + 450	2	Glyphosate × 1[d]	450	1,460
3	2,4-D[b] + glyphosate[c]	560 + 450	3	Ethalfluralin[b]	1, 100	2,110
3	2,4-D[b] + glyphosate[c]	560 + 450	4	Ethalfluralin[b], sethoxydim + ethametsulfuron + clopyralid[e]	1, 100, 200 + 22 + 150	2,482
3	2,4-D[b] + glyphosate[c]	560 + 450	5	Sethoxydim + ethametsulfuron[e]	200 + 22	1,232

[a] Clopyralid was Lontrel®, 360 g ai/L;[5] 2,4-D was 2,4-D amine 500®, 470 g ai/L;[5] ethalfluralin was Edge®, 5% ai;[5] ethametsulfuron was Muster®, 75% ai;[6] glyphosate was Roundup Transorb®, 360 g ae/L;[4] and sethoxydim was Poast Ultra®, 450 g ai/L.[7]

[b] Herbicides were applied in fall.

[c] Herbicides were applied in spring before seeding canola.

[d] Glyphosate was applied twice (× 2) at the two- to four- and five- to six-leaf or once (× 1) at the two- to four-leaf stage of canola.

[e] Herbicides were applied as tank mixtures after canola emergence in spring.

Herbicides and rates are indicated in Table 2. With the exception of ethalfluralin (granular formulation applied with a spreader on the soil surface in fall), all herbicides were applied in a water volume of 110 L/ha with flat-fan nozzles at a pressure of 275 kPa at Beaverlodge and Lacombe and 207 kPa at Lethbridge. The first in-crop glyphosate application was at the two- to four-leaf stage of canola, and the second was at the five- to six-leaf stage. All other in-crop herbicides were applied at the two- to four-leaf stage. Experiments were fertilized according to soil test recommendations for canola. Fertilizers were applied as a side-band (Beaverlodge and Lacombe) or a midrow band (Lethbridge).

Data Collection. At approximately 6 wk after the last herbicide application, weed biomass samples were harvested from two 0.5-m^2 quadrats in each plot. Canola was harvested at maturity and a seed subsample (approximately 1,000 g) was collected for further analysis. Percent dockage (weed seed and other extraneous harvested material) was determined. A subsample of approximately 1,000 grams from each plot was used to determine seed weight and oil and protein concentrations, which were determined using a near infrared reflectance spectrometer[8] and carbon/nitrogen determinator,[9] respectively.

Economic Analysis. Net economic return for each herbicide treatment was calculated from the equation:

$$N = (YP) - (T + S + H + A) \qquad [1]$$

where N is the net economic return (Canadian \$/ha), Y is canola seed yield (kg/ha), P is the market price of canola seed (Canadian \$/ha), T equals the technology-use agreement cost (Canadian \$/ha) for the glyphosate-resistant system, S is the seed cost (Canadian \$/ha), H equals the herbicide cost (Canadian \$/ha), and A is the herbicide application cost (Canadian \$/ha). Herbicide costs/ha for single applications at the rates used in the study (Table 2) were based on 2005 prices of $7.50 (2,4-D), $12.24 (glyphosate), $49.28 (ethalfluralin), $38.37 (sethoxydim), $59.87 (ethametsulfuron), and $56.08 (clopyralid). Other assumptions were that $P = \$0.30$/kg; $T = \$37.12$/ha; $S = \$77.28$ and $73.92/ha for glyphosate-resistant and nonresistant canola seed, respectively; and $A = \$10.00$/ha.

Experimental Design and Data Analysis. The two-factor (three by five treatments) experiment was designed

[5] Dow AgroSciences Canada Inc. #201, 1144-29 Avenue Northeast, Calgary, AB T2E 7P1, Canada.

[6] Dupont Canada Inc., 444-72 Avenue Southeast, Calgary, AB T2C 2C1, Canada.

[7] BASF Canada, 345 Carlingview Drive, Toronto, ON M9W 6N9, Canada.

[8] FOSS, North America Inc., 11 Edvac Drive, Unit 10, Brampton, ON L6S 5W6, Canada.

[9] LECO Instruments Ltd., 6185 Danville Road, Mississauga, ON L5T 2HT, Canada.

as a randomized complete-block with four replicates. Three pre-seed herbicide treatments were allocated to Factor 1, and five in-crop treatments were allocated to Factor 2 (Table 2). The in-crop treatments included fall-applied ethalfluralin because its activity would likely persist and affect weed seed that germinated after the crop emerged.

Canola yield (kg/ha), net return ($/ha), weed biomass ($g/m^2$), and dockage (%) data were analyzed using PROC MIXED (random-effects model) of SAS (Littel et al. 1996). Replicate and location-by-year combinations (location–years) were considered as random effects and herbicide treatments as fixed effects. With location–years as a random effect, general conclusions and recommendations could be made on the relative merits of the herbicide regimes beyond the specific experiment locations. Data were also analyzed using PROC GLM (fixed-effects model) with location–years as a fixed effect. This methodology allowed for a more exploratory analysis to determine whether significant interactions occurred between location–years and herbicide regimes and whether the interactions changed the nature of the conclusions derived from the random-effects model. Treatment means were compared using single degrees of freedom contrasts. Differences were deemed significant at $\alpha < 0.05$.

RESULTS AND DISCUSSION

A severe hailstorm at Lacombe in 2001 and operational problems at Beaverlodge in 2002 affected data collection and compromised the reliability of the conclusions. Thus, all data for Beaverlodge 2002 and canola yield and net-return data for Lacombe 2001 were not included in the statistical analyses.

Location–Years As Fixed Effects. Analysis of the data using the fixed-effects model indicated that there was a consistent three-way interaction (location by year by in-crop herbicide treatment, $P < 0.01$) for all variables. Further analysis indicated that the effects of four of the in-crop herbicide treatments were consistent among location–years. The exception was sethoxydim plus ethametsulfuron (treatment 5, Table 2), which had variable effects on weed biomass among years at each location. Total weed biomass following this treatment averaged only 300 kg/ha at Beaverlodge in 2001 and Lacombe and Lethbridge in 2003 compared with 2,170 kg/ha when averaged over the other location–years (data not shown). This response was largely because of variable control of volunteer barley by sethoxydim among years.

Table 3. P values from the ANOVA for the effects of herbicide treatments on weed and canola variables. Numbers in bold indicate significance at $P < 0.05$.

Factor[a]	Weed biomass	Dockage	Canola yield	Net return
Pre-seed	**0.0002**	**0.0133**	**0.0001**	**0.0085**
In-crop	**<0.0001**	**<0.0001**	**<0.0001**	**<0.0001**
Pre-seed + in-crop	0.3395	0.3682	0.3331	0.3330

[a] See Table 2 for specific herbicide treatments assigned to pre-seed and in-crop.

In a previous study, control of volunteer cereals in canola with sethoxydim also varied considerably among locations and years (Chow et al. 1983), but the reasons for this were unclear.

The fixed-effects model also indicated a significant ($P < 0.05$) location by pre-seed treatment interaction for weed biomass but not for the other variables. This response occurred because differences in weed biomass among the pre-seed treatments were less pronounced at Lacombe than at the other locations (data not shown). Both interactions accounted for relatively small proportions of the total variance, and neither changed the nature of the conclusions derived from the random-effects model. Thus, further discussion will be restricted to the results of the data analysis with the random-effects model.

Location–Years As Random Effects. The analysis of variance with the random-effects model indicated significance of main effects (pre-seed and in-crop herbicide treatment factors) for all variables, but none of the interactions were significant (Table 3). Thus, further analysis was conducted within each factor.

Averaged over in-crop herbicide treatments, weed biomass (457 vs. 1,004 kg/ha) and dockage (9 vs. 12%) were lower, and canola yield (1,646 vs. 1,499 kg/ha) and net return (290 vs. 251 $/ha) were higher when glyphosate was applied pre-seed in the spring compared with 2,4-D applied in the fall (Table 4). Furthermore, a combination of both 2,4-D in fall and pre-seed glyphosate in spring did not improve weed control, canola yield, or net return compared with the pre-seed glyphosate treatment alone. The results suggest that, under zero tillage, a pre-seed glyphosate application will likely improve weed control and canola productivity whether or not 2,4-D is applied in fall. Thus, a fall 2,4-D application may be unnecessary if there is a high likelihood that glyphosate will be applied before seeding canola. In a previous study, the relative benefits of a pre-seed compared with an early in-crop glyphosate application depended on how early canola was seeded (Clayton et al. 2002). In that study, limited weed emergence following

Table 4. Effect of pre-seed herbicide treatments on weed and canola variables and on net return.[a] Numbers in bold indicate significance at P < 0.05.

Treatment	Herbicide	Weed biomass	Dockage	Canola yield	Net return
		kg/ha	%	kg/ha	Canadian $/ha
1	2,4-D[b]	1,004	12	1,499	251
2	Glyphosate[c]	457	9	1,646	290
3	2,4-D[b] + glyphosate[c]	590	9	1,679	282
Treatment contrasts		P values			
1 vs. 2		**<0.0001**	**0.0082**	**0.0011**	**0.0035**
1 vs. 3		**0.0027**	**0.0152**	**<0.0001**	**0.0199**
2 vs. 3		0.3308	0.8466	0.4663	0.5741

[a] Data were averaged over in-crop herbicide treatments (see Table 2).

[b] 2,4-D was applied in fall before seeding canola in spring.

[c] Glyphosate was applied in spring before seeding canola.

early seeding favored an early in-crop compared with a pre-seed glyphosate application.

Glyphosate applied once or twice in-crop provided superior weed control, lower dockage, and higher canola yield than ethalfluralin applied in fall or an in-crop mixture of sethoxydim and ethametsulfuron (Table 5). This finding is in agreement with a previous study where the glyphosate-resistant system was also shown to result in superior weed control and sometimes higher canola yields than a conventional treatment of sethoxydim and ethametsulfuron (Harker et al. 2000).

The relatively poor weed control and reduced canola yields with the nonherbicide resistant regimes (compared with the glyphosate-resistant system) reflects the difficulty in controlling the broad spectrum of weeds that were present at each location (Tables 1 and 5). For example, ethalfluralin was ineffective on the cruciferous weeds, field pennycress and wild mustard (*Sinapis arvensis* L.), and poorly controlled volunteer barley, whereas the sethoxydim plus ethametsulfuron mixture effectively controlled these weeds but had little or no activity on many of the weeds controlled by ethalfluralin including wild buckwheat and common lambsquarters (*Chenopodium album* L.).

For these reasons, many canola growers in western Canada have traditionally followed a preplant ethalfluralin application with one or more in-crop herbicides. In our study, preplant ethalfluralin followed by sethoxydim, ethametsulfuron, and clopyralid applied in-crop resulted in similar weed biomass, dockage and canola yields as one or two in-crop glyphosate applications; and superior weed control and canola yields compared with ethalflur-

Table 5. Effect of in-crop herbicide treatments on weed and canola variables.[a] Numbers in bold indicate significance at P < 0.05.

Treatment	Herbicide	Weed biomass	Dockage	Canola yield	Net return
		kg/ha	%	kg/ha	Canadian $/ha
1	Glyphosate × 2[b]	136	7	1,688	321
2	Glyphosate × 1[b]	296	8	1,722	354
3	Ethalfluralin[c]	1,393	12	1,487	286
4	Ethalfluralin[c] sethoxydim + ethametsulfuron + clopyralid[d]	410	10	1,630	165
5	Sethoxydim + ethametsulfuron[d]	1,182	15	1,512	245
Treatment contrasts		P values			
1 vs. 2		0.3635	0.5199	0.5548	0.0625
1 vs. 3		**<0.0001**	**0.0004**	**0.0006**	**0.0464**
1 vs. 4		0.1215	0.0593	0.3189	**<0.0001**
1 vs. 5		**<0.0001**	**<0.0001**	**0.0024**	**<0.0001**
2 vs. 3		**<0.0001**	**0.0036**	**<0.0001**	**0.0001**
2 vs. 4		0.5235	0.2171	0.1161	**<0.0001**
2 vs. 5		**<0.0001**	**<0.0001**	**0.0004**	**<0.0001**
3 vs. 4		**<0.0001**	0.0897	**0.0141**	**<0.0001**
3 vs. 5		0.2310	0.0953	0.6674	**0.0172**
4 vs. 5		**<0.0001**	**0.0008**	**0.0423**	**<0.0001**

[a] Data were averaged over pre-seed herbicide treatments (see Table 1).

[b] Glyphosate was applied twice (× 2) at the two- to four- and five- to six-leaf or once (× 1) at the two- to four-leaf stage of canola.

[c] Ethalfluralin was applied in fall.

[d] Herbicides were applied as tank mixtures after canola emergence in spring.

alin or the sethoxydim and ethametsulfuron in-crop combination (Table 5).

The in-crop glyphosate applications (glyphosate-resistant system) resulted in higher net revenues than any of the other treatments (Table 5). Net return with the single in-crop glyphosate application was more than twice that with the four-herbicide combination (Table 5, treatments 2 and 4). The inclusion of clopyralid in treatment 4 may have unnecessarily increased the cost of the system because Canada thistle was not present at any of the locations, and infestations of perennial sowthistle (*Sonchus arvensis* L.) were relatively minor. However, if its cost was omitted from the economic analysis, there was still a 63% increase in net return with the single glyphosate application. The lower net return with ethalfluralin and sethoxydim plus ethametsulfuron compared with the glyphosate-resistant system (Table 5) was mainly due to reduced canola yields caused by weed competition rather than to the relative costs of the systems.

There was no advantage to applying glyphosate twice compared with once in-crop in terms of weed biomass (136 vs. 296 kg/ha), dockage (7 vs. 8%), or canola yields (1,688 vs. 1,722 kg/ha) (Table 5). Net returns were also similar ($P = 0.063$) (321 vs. 354 $/ha) because differences were deemed significant at the commonly used $\alpha < 0.05$. However, if a less-conservative test of significance was employed (e.g., $\alpha < 0.10$), the net return would have been 10% higher for the single compared with the double in-crop glyphosate application (Table 5). Seed weight and/or oil or protein content of canola was not differentially affected by any of the herbicide treatments (data not shown).

The results of the study indicate that the glyphosate-resistant canola system was as good or superior to several more traditional herbicide regimes in terms of maximizing weed control and canola yield. More importantly, in spite of the technology-use agreement and higher seed costs, the glyphosate system resulted in higher net revenues than the other herbicide regimes, especially when glyphosate was applied only once in-crop. These findings are in agreement with the results of a study with glyphosate-resistant soybean [*Glycine max* (L.) Merr.], in which a single in-crop glyphosate application optimized weed control and crop yield and resulted in better economic returns than alternative herbicide treatments (Ivany 2004). In other studies with soybean, however, results were more variable and sometimes inconclusive (Reddy and Whiting 2000; Shaw et al. 2001; Webster et al. 1999). Similarly, in corn (*Zea mays* L.) (Ferrell and Witt 2002) and cotton (*Gossypium hirsutum* L.) (Culpepper and York 1999), weed control, yield, and economic return differed little between the glyphosate-resistant system and conventional herbicide regimes. In our study with canola, the superior economic returns with the glyphosate-resistant system are reflective of the general lack of cost-effective herbicides for broad spectrum weed control in nonherbicide-resistant canola. In the other crops, however, where economical weed control is more feasible, herbicide-resistant systems may be more difficult to justify economically.

In previous studies with canola (Harker et al. 2000) and sugar beet (*Beta vulgaris* L.) (Kniss et al. 2004), differences between the glyphosate-resistant system and conventional herbicide regimes were often influenced by the different yield potentials of the cultivars. In our study, the confounding effect of canola cultivar was removed by using the glyphosate-resistant cultivar for all herbicide treatments. This was an important feature of the study because the introduction of new canola cultivars every year limits the importance of a particular cultivar at a given point in time (Harker et al. 2000).

The relative economic merits of the glyphosate-resistant compared with the other herbicide-resistant canola systems registered in western Canada were not determined in this study. In a previous agronomic comparison among the different herbicide-resistant systems, weed control was found to be better with glyphosate followed by the imidazolinone- and glufosinate-resistant systems (Harker et al. 2000). Furthermore, the latter herbicides sometimes provided inferior weed control to a standard treatment of sethoxydim plus ethametsulfuron. In another study, however, canola yields did not vary among the three herbicide-resistant systems (Harker et al. 2004), suggesting that the relative economics of the three systems may be determined mainly by their respective costs rather than their agronomic effectiveness.

The amount of herbicide active ingredient entering the environment varied with the herbicide regime but was lower with the glyphosate-resistant system than with most of the traditional regimes, especially when glyphosate was applied only once in-crop (Table 1). Assuming a pre-seed glyphosate (but no 2,4-D) application, even when glyphosate was applied twice in-crop, the total amount of active ingredient was lower (1,353 vs. 1,922 g/ha) than with the four-herbicide in-crop combination. This finding suggests that risk in terms of herbicide load on the environment may be less with the glyphosate-resistant canola system than with other herbicide regimes that have been traditionally used in canola. Other studies have also indicated that environmental and ecological risks, including groundwater contamination, were less with glyphosate than with most other active ingredients (Peterson and Hulting 2004).

Thus, there is relatively little or no short-term agronomic, economic, or environmental risk associated with the adoption of the glyphosate-resistant canola system in western Canada. On the contrary, weed control and net returns were superior with the glyphosate-resistant system than with most of the other herbicide regimes. The employment of glyphosate and other herbicide-resistant canola systems may also delay the development of herbicide-resistant weed biotypes in that the technology provides alternative in-crop mechanisms of action (Harker et al. 2000). In some cases, wild oat populations in western Canada have become resistant to graminicides with as many as four different mechanisms of action (Beckie et al. 1999). On the other hand, there is concern that the risk of selecting for glyphosate-resistant weeds in western Canada may increase with the widespread adoption of the glyphosate-resistant canola system. This risk may be higher under zero-compared with conventional-tillage systems because multiple glyphosate applications are more likely. There is increasing evidence that timing of the glyphosate applications based on rational assessments of weed emergence patterns is more important than the total number of applications in both canola (Clayton et al. 2002; Harker et al. 2004; Johnson et al. 2002) and soybean (Swanton et al 2000). With appropriate timing, our study and others also indicate that two glyphosate applications (pre-seed and once in-crop, or twice in-crop) would, in most cases, be sufficient to optimize weed control, crop yield, and economic return.

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