Weed Technology. 2004. Volume 18:711–718

Control of Volunteer Herbicide-Resistant Wheat and Canola[1]

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Abstract: Volunteer crops resistant to glyphosate and other herbicides pose a potential problem for Pacific Northwest (PNW) growers that rely on glyphosate for control of volunteer crops and weeds during fallow and before planting. Herbicides for control of volunteer herbicide-resistant wheat and canola in PNW conservation tillage systems were evaluated during 2000 and 2001 near Ralston, WA, and Moscow, ID. Paraquat + diuron controlled glyphosate- and imidazolinone-resistant wheat ≥90%, and glyphosate controlled imidazolinone-resistant wheat 88 to 96% 14 d after treatment (DAT). Glyphosate- and imidazolinone-resistant wheat were controlled only 58 to 85% with quizalofop-P and clethodim 14 DAT. By 21 DAT, imidazolinone-resistant wheat control with clethodim and quizalofop-P was ≥93%, but the longer time period required for control to reach an acceptable level could increase disease and insect problems associated with volunteer wheat. Volunteer glyphosate-resistant canola was controlled 92 and 97% 14 DAT and 76 and 98% 21 DAT with paraquat and paraquat + diuron, respectively. Treatments that contained glyphosate controlled imidazolinone- and glufosinate-resistant canola >84% 14 DAT. By 21 DAT, control of imidazolinone- and glufosinate-resistant canola was 94 to 98% with paraquat + diuron and all glyphosate treatments, except glyphosate–isopropylamine salt (IPA) + glufosinate (88 to 93%) and glyphosate-IPA + paraquat (67 to 85%). In these studies, paraquat + diuron was the best alternative to glyphosate for controlling volunteer herbicide-resistant wheat and canola.

Nomenclature: Clethodim; diuron; glufosinate; glyphosate; imidazolinone; paraquat; quizalofop-P; canola, *Brassica napus* L. 'DKL 27-20', 'Phoenix', 'Pioneer 45A71'; wheat, *Triticum aestivum* L. 'Bobwhite', 'FS-4 IR'.

Additional index words: Direct seeding, glufosinate resistant, glyphosate resistant, green-bridge, imidazolinone resistant.

Abbreviations: ACCase, acetyl coenzyme A carboxylase; DA, diammonium salt; DAT, days after treatment; HRC, herbicide-resistant crops; IPA, isopropylamine salt; PNW, Pacific Northwest.

INTRODUCTION

Farmers have readily adopted herbicide-resistant crops (HRC) into their production systems. Growers in Canada and the Midwestern United States are planting millions of hectares of herbicide-resistant canola, corn, and soybean (James 2000). Bromoxynil-, glyphosate-, glufosinate-, and imidazolinone-resistant canola cultivars are currently available and imidazolinone-resistant wheat is available on a limited basis to U.S. and Canadian farmers. Glyphosate-resistant spring wheat cultivars are expected to be released to growers within 5 yr (Lyon et al. 2002). Pacific Northwest (PNW) growers likely will adopt HRC quickly and with the same enthusiasm as corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] growers. When used properly, HRC can provide growers with an unprecedented ability to control some of their most troublesome weeds. Glyphosate applied to glyphosate-resistant wheat can be used to control difficult annual grass weeds, such as members of the *Aegilops*, *Avena*, *Bromus*, *Lolium*, *Poa*, and *Secale* genera (Lyon et al. 2002). If used improperly, HRC, like other weed control practices, could result in ineffective weed control through weed species shifts and selection of herbicide-resistant weed biotypes (Ogg and Isakson 2001; Radosevich et al. 1992). As with any new technology, farmers will require specific training on how to incorporate HRC into a weed management program for their particular cropping system (Marshall 1998). There currently is little or no information on how to safely and effectively incorporate HRC into PNW cropping systems.

Seed shatter before harvest combined with seed lost

[1] Received for publication June 18, 2003, and in revised form February 17, 2004. Published with approval of the Agricultural Experiment Station, University of Idaho, as Journal Article 03730.

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through the combine during harvest of herbicide-resistant cultivars may result in HRC volunteer in succeeding crops (Lutman 1993). Volunteer crop plants can reduce yields of the planted crop, reduce host insects or disease, interfere with harvest, and reduce the quality of the harvested crop (Ogg and Parker 2000). Volunteer cereals can act as a green-bridge or host for numerous plant pathogens and insects between cropping seasons (Cook and Veseth 1991; Veseth 1993a). As volunteer wheat plants die from a herbicide application, their roots become more susceptible to pathogens, resulting in a sharp and temporary increase in root pathogen activity. If the newly planted cereal crop is in early growth stages during this period, there is a high probability of crop loss from root disease (Veseth 1993b). Smiley et al. (1992) found that disease incidence was least when glyphosate was applied 3 wk before planting barley (*Hordeum vulgare* L.) and greatest when applied 3 d before planting. Volunteer wheat plants should be dead at least 3 wk before the emergence of fall-seeded wheat to reduce insect and disease problems associated with the green-bridge (Cook and Veseth 1991). Slow or incomplete volunteer wheat control could result in a green-bridge being present during seeding of cereal crops.

The ability of herbicide-resistant wheat and canola to hybridize with conventional cultivars and weedy relatives is an additional concern (Hall et al. 2000; Seefeldt et al. 1998). Uncontrolled herbicide-resistant volunteer crop plants can act as pollen sources and contaminate non–herbicide-resistant crops or transfer resistance to weedy relatives.

Traditionally, PNW growers have relied on tillage in conventionally tilled cropping systems and glyphosate in conservation tillage systems to control volunteer crops and weeds before planting the next crop (Thill 1996). Glyphosate is the herbicide of choice for control of volunteer crops and weeds because it is effective, relatively fast acting, dependable, economical, and has no soil activity (Bayliss 2000; Ogg and Isakson 2001). Volunteer glyphosate-resistant wheat and canola plants will pose a problem for growers who rely solely on glyphosate for total vegetation control before planting in conservation tillage systems. In addition, non–acetolactate synthase-inhibiting herbicides will be required to control imidazolinone-resistant volunteer crop plants in subsequently planted imidazolinone-resistant crops.

Control of herbicide-resistant volunteer wheat and canola plants must be addressed before these crops are widely adopted in the PNW (Mallory-Smith and Hyslop 1999). Currently, little research has been conducted to identify effective herbicides that will control glyphosate-resistant volunteer wheat and canola plants in conservation tillage systems. Growers using conservation tillage systems must have herbicides that adequately control glyphosate-resistant volunteer plants or they will have to resort to tillage, which could increase soil erosion, reduce water infiltration into the soil, decrease soil organic matter, and increase production costs (Schillinger et al. 1999; Young et al. 1994). No-till growers recently were surveyed regarding the use of glyphosate-resistant wheat, and they overwhelmingly responded that they would not use this technology unless an inexpensive and effective alternative to glyphosate for volunteer wheat control was available (Ogg and Isakson 2001). The purpose of this study was to identify herbicides that effectively control volunteer herbicide-resistant canola and wheat before planting in PNW conservation tillage systems.

MATERIALS AND METHODS

Field experiments were conducted in the spring of 2000 and 2001 near Ralston, WA, and Moscow, ID. Soil at Moscow was Westlake-latahco silt loam with a pH of 5.3 to 5.4 and 3.2% organic matter content. At Ralston, soil was a Ritzville silt loam with a pH of 7.0 to 7.1 and 2.1 to 2.2% organic matter content.

The experimental design for each year and site was a randomized complete block–split block with four replications. Main block treatments (volunteer crops) were 4.5 by 34.1 m, and split-block treatments (herbicides) were 2.4 by 4.5 m. All crops were seeded into standing cereal stubble using a no-till drill equipped with shank-mounted openers[3] spaced 25 cm apart to simulate volunteer crop plants in conservation tillage systems. 'FS-4 IR' imidazolinone-resistant winter wheat (CFW) and 'Bobwhite' glyphosate-resistant spring wheat (RRW) were seeded 3 cm deep at 28 kg/ha, and 'DKL 27-20' glyphosate-resistant canola (RRC), 'Pioneer 45A71' imidazolinone-resistant canola (CFC), and 'Phoenix' glufosinate-resistant canola (LLC) were seeded 1.5 cm deep at 1.5 kg/ha in 2000 and 10 kg/ha in 2001. The canola seeding rate was increased in 2001 because of poor crop establishment in 2000. Seeding dates were March 31, 2000, and April 5, 2001, at Ralston and May 8, 2000, and April 23, 2001, at Moscow. Canola was reseeded on May 10, 2001, at Ralston because emergence was low and frost damaged emerged seedlings. Herbicides (Table

[3] Flexi-coil Stealth™ openers, St. John Hardware & Implement, 3 Front Street, St. John, WA 99171.

Table 1. Herbicide treatments and rates applied in volunteer herbicide-resistant crop studies near Moscow, ID, and Ralston, WA, in 2000 and 2001.[a]

Treatment	Rate
Glyphosate-IPA[b] + AMS[c]	0.43 kg ae/ha + 5% v/v
Glyphosate/2,4-D[d] + AMS	0.42/0.71 kg ae/ha + 5% v/v
Glyphosate/dicamba[e] + AMS	0.45/0.11 kg ae/ha + 5% v/v
Paraquat + NIS[f]	0.56 kg ai/ha + 0.25% v/v
Glufosinate	0.49 kg ai/ha
Glyphosate-DA[g] + AMS	0.43 kg ae/ha + 5% v/v
Glyphosate-IPA + glufosinate + AMS	0.43 kg ae/ha + 0.49 kg ai/ha + 5% v/v
Glyphosate-IPA + paraquat + AMS + NIS	0.43 kg ae/ha + 0.56 kg ai/ha + 5% v/v + 0.25% v/v
Paraquat + diuron + NIS	0.56 kg ai/ha + 0.28 kg ai/ha + 0.25% v/v
Quizalofop-P + NIS	0.062 kg ai/ha + 0.25% v/v
Glyphosate-IPA + quizalofop-P + AMS + NIS	0.43 kg ae/ha + 0.062 kg ai/ha + 5% v/v + 0.25% v/v
Clethodim + COC[h]	0.104 kg ai/ha + 0.5% v/v
Glyphosate-IPA + clethodim + AMS + COC	0.43 kg ae/ha + 0.104 kg ai/ha + 5% v/v + 0.5% v/v
Untreated control	

[a] Abbreviations: IPA, isopropylamine salt; AMS, ammonium sulfate; NIS, nonionic surfactant; DA, diammonium salt; COC, crop oil concentrate.

[b] Glyphosate isopropylamine salt, Roundup ULTRA™ RT (Monsanto Company, 800 North Lindbergh Boulevard, St. Louis, MO 63167).

[c] Five percent v/v is equivalent to 7.7 kg/378.5 L spray volume. Bronc Max (Wilbur-Ellis Company, 345 California Street, San Francisco, CA 94104).

[d] Applied as the commercial formulation Landmaster BW® (Monsanto Company).

[e] Applied as the commercial formulation Fallow Master® (Monsanto Company).

[f] R-11® (Wilbur-Ellis Company).

[g] Glyphosate diammonium salt, Touchdown® (Syngenta, 1800 Concord Pike, Wilmington, DE 19850).

[h] Moract® (Wilbur-Ellis Company).

1) were applied with a CO_2-pressurized backpack sprayer calibrated to deliver 94 L/ha at 275 kPa to wheat in the four- to eight-leaf stage and to 12- to 20-cm-tall canola. At Ralston, wheat and canola were treated on May 15, 2000. In 2001, wheat was treated on May 31 and canola was treated on June 13. At Moscow, both crops were treated on June 11, 2000, and June 6, 2001.

Data were not collected in one replication at Ralston in 2001 because migratory grasshopper [*Melanoplus sanguinipes* (Fabricius)] destroyed stands. Plots were treated with cabaryl(1-napthyl-*N*-methylcarbamate) at 1.12 kg/ha to prevent further damage.

Control (necrosis) of volunteer crops was evaluated visually 14 and 21 d after treatment (DAT), on a scale of 0% (no control) to 100% (complete control). Aboveground crop biomass samples were collected 28 DAT from a 0.25-m^2 area randomly located within each plot. Green tissue was clipped near the soil surface, placed in paper bags, dried at 60 C for 72 h, and weighed. Canola biomass was not collected in 2000 at Ralston because stand establishment was very poor. Experiments were terminated immediately after biomass collection to prevent seed production.

All data were subjected to ANOVA using general linear models procedures (SAS 1994). Arcsine transformation of percentage data did not affect the analysis and is not presented. Means for control of volunteer crop plants 14 and 21 DAT were separated using Fisher's protected LSD. Biomass was analyzed as a percentage of the untreated control, and means were separated using Fisher's protected LSD. Contrasts were conducted to compare RRW vs. CFW control 14 and 21 DAT with clethodim, paraquat + diuron, and quizalofop and CFC vs. RRC and LLC control 14 and 21 DAT with paraquat and paraquat + diuron.

RESULTS AND DISCUSSION

The crop by herbicide treatment interaction was significant ($P < 0.001$), and thus data were analyzed by individual volunteer crop (data not shown). For analysis of pooled data, year and location combinations were considered as random effects and herbicide treatment was tested using the appropriate term as specified in Carmer et al. (1989). When year by treatment, location by treatment, or location by year by treatment interactions occurred during the analysis of individual volunteer crop data, treatment means for individual years and locations were plotted to investigate the cause of the interaction. When interactions were minimal and did not practically affect the ranking of treatments, data were pooled over location and year for analysis, and when interactions were complex, data were analyzed for individual locations and years.

Glyphosate-Resistant Wheat. Glyphosate–isopropylamine salt (IPA) alone, glyphosate–diammonium salt (DA), glyphosate/2,4-D, and glyphosate/dicamba did not control volunteer RRW and were not included in the ANOVA for control 14 and 21 DAT. There was a com-

Table 2. The effect of herbicide treatment on volunteer glyphosate- and imidazolinone-resistant wheat (RRW and CFW, respectively) control 14 DAT near Moscow, ID, and Ralston, WA, in 2000 and 2001 and control 21 DAT pooled over locations and years.[a]

	Control									
	14 DAT									
	RRW				CFW					
	Moscow		Ralston		Moscow		Ralston		21 DAT	
Treatment	2000	2001	2000	2001	2000	2001	2000	2001	RRW	CFW
	% control									
Glyphosate-IPA[b] + AMS[c]	—[d]	—	—	—	96	94	86	88	—	95
Glyphosate/2,4-D[e] + AMS	—	—	—	—	94	94	89	93	—	96
Glyphosate/dicamba[f] + AMS	—	—	—	—	95	95	85	92	—	94
Paraquat + NIS[g]	78	85	86	82	75	76	80	88	58	63
Glufosinate	64	63	60	52	48	50	38	55	50	46
Glyphosate-DA[h] + AMS	—	—	—	—	91	93	85	92	—	95
Glyphosate-IPA + glufosinate + AMS	66	63	69	53	74	75	60	57	45	79
Glyphosate-IPA + paraquat + AMS + NIS	78	79	86	80	50	66	56	53	62	66
Paraquat + diuron + NIS	90	97	93	92	99	95	99	96	90	93
Quizalofop-P + NIS	79	71	58	83	78	63	61	83	93	93
Glyphosate-IPA + quizalofop-P + AMS + NIS	74	71	66	85	95	95	88	95	95	97
Clethodim + COC[i]	83	63	60	85	73	65	71	78	94	95
Glyphosate-IPA + clethodim + AMS + COC	87	75	73	83	94	93	91	95	94	96
LSD (0.05)	15	10	11	7	11	7	7	6	6	4

[a] Abbreviations: DAT, days after treatment; IPA, isopropylamine salt; AMS, ammonium sulfate; NIS, nonionic surfactant; COC, crop oil concentrate; DA, diammonium salt.

[b] Glyphosate isopropylamine salt, Roundup ULTRA™ RT (Monsanto Company).

[c] Five percent v/v is equivalent to 7.7 kg/378.5 L spray volume. Bronc Max (Wilbur-Ellis Company).

[d] Dashes indicate that the treatment was not included in data analysis because it did not control the volunteer crop.

[e] Applied as the commercial formulation Landmaster BW® (Monsanto Company).

[f] Applied as the commercial formulation Fallow Master® (Monsanto Company).

[g] R-11® (Wilbur-Ellis Company).

[h] Glyphosate diammonium salt, Touchdown® (Syngenta).

[i] Moract® (Wilbur-Ellis Company).

plex location by treatment by year interaction ($P < 0.0001$) for volunteer RRW control 14 DAT (data not shown), and data were analyzed by individual locations and years. Paraquat + diuron controlled volunteer RRW 90 to 97% 14 DAT at both locations in both years (Table 2). Paraquat alone and glyphosate-IPA + paraquat at Moscow and Ralston in 2000 and 2001 controlled RRW 78 to 86% 14 DAT. RRW control 14 DAT with treatments containing quizalofop-P or clethodim was 74 to 87% at Moscow in 2000, 63 to 75% at Moscow in 2001, 58 to 73% at Ralston in 2000, and 83 to 85% at Ralston in 2001. The variation in control with quizalofop-P and clethodim was likely due to differences in growth rate and environment before and immediately after application. Environmental factors, such as drought stress, can decrease the activity of acetyl coenzyme A carboxylase (ACCase)–inhibiting herbicides more than the activity of glyphosate (Lyon et al. 2002). RRW was controlled 52 to 69% with glufosinate and glyphosate-IPA + glufosinate at Moscow and Ralston in 2000 and 2001.

There was a significant treatment by year interaction ($P = 0.0306$) for volunteer RRW control 21 DAT (data not shown). The interaction was due to a change in the rank of treatments between locations and years caused by 10 to 12 percentage points greater control with paraquat and glyphosate-IPA + paraquat at Ralston in 2001 compared with other locations and years. The greater level of control was attributed to less regrowth after burndown with paraquat. Control of RRW with other treatments was similar between locations and years; thus, data were pooled over locations and years (Table 2). Volunteer RRW was controlled 90 to 95% with paraquat + diuron and treatments containing clethodim or quizalofop-P 21 DAT. All other treatments controlled volunteer RRW only 45 to 62% 21 DAT.

RRW biomass was reduced 91 to 96% by paraquat + diuron and treatments containing quizalofop-P and clethodim, 73% by paraquat, 71% by glyphosate-IPA + paraquat, 47% by glufosinate, and 48% by glyphosate-IPA + glufosinate (Table 3). Biomass of volunteer RRW ranged from 82 to 100% of the untreated control in plots treated with glyphosate-IPA, glyphosate-DA, glyphosate/2,4-D, and glyphosate/dicamba.

Volunteer RRW control 14 DAT was 58 to 85% with

Table 3. The effect of herbicide treatment on volunteer glyphosate- and imidazolinone-resistant wheat (RRW and CFW, respectively) biomass 28 DAT near Moscow, ID, and Ralston, WA, in 2000 and 2001.[a]

	Biomass 28 DAT				
	RRW	CFW			
		Moscow		Ralston	
Treatment	Pooled over locations and years	2000	2001	2000	2001
	% of the untreated control				
Glyphosate-IPA[b] + AMS[c]	100	1	2	6	15
Glyphosate/2,4-D[d] + AMS	90	17	2	3	7
Glyphosate/dicamba[e] + AMS	97	11	3	3	1
Paraquat + NIS[f]	27	32	29	16	34
Glufosinate	53	41	22	23	55
Glyphosate-DA[g] + AMS	82	3	0	7	10
Glyphosate-IPA + glufosinate + AMS	52	10	8	18	40
Glyphosate-IPA + paraquat + AMS + NIS	29	44	26	18	47
Paraquat + diuron + NIS	9	22	4	2	4
Quizalofop-P + NIS	6	7	4	3	7
Glyphosate-IPA + quizalofop-P + AMS + NIS	6	4	2	0	2
Clethodim + COC[h]	6	4	4	3	1
Glyphosate-IPA + clethodim + AMS + COC	4	4	2	2	6
LSD (0.05)	15	21	7	10	15

[a] Abbreviations: DAT, days after treatment; IPA, isopropylamine salt; AMS, ammonium sulfate; NIS, nonionic surfactant; DA, diammonium salt; COC, crop oil concentrate.

[b] Glyphosate isopropylamine salt, Roundup ULTRA™ RT (Monsanto Company).

[c] Five percent v/v is equivalent to 7.7 kg/378.5 L spray volume. Bronc Max (Wilbur-Ellis Company).

[d] Applied as the commercial formulation Landmaster BW® (Monsanto Company).

[e] Applied as the commercial formulation Fallow Master® (Monsanto Company).

[f] R-11® (Wilbur-Ellis Company).

[g] Glyphosate diammonium salt, Touchdown® (Syngenta).

[h] Moract® (Wilbur-Ellis Company).

clethodim and quizalofop-P, whereas control with paraquat + diuron was 90 to 97%. Paraquat + diuron provided more rapid and consistent control than other herbicides in this study and based on efficacy appears to be the best alternative to glyphosate for volunteer RRW control.

Imidazolinone-Resistant Wheat. Data for volunteer CFW control 14 DAT were analyzed by individual locations because the location by treatment by year interaction was significant ($P < 0.0001$) (data not shown). Volunteer CFW was controlled 85 to 96% by all treatments containing glyphosate, except for glyphosate-IPA + glufosinate (57 to 75%) and glyphosate-IPA + paraquat (50 to 66%) 14 DAT at Moscow and Ralston in 2000 and 2001 (Table 2). Tank mixing paraquat or glufosinate with glyphosate reduced control 20 to 46 percentage points, respectively, compared with glyphosate alone. Glufosinate and paraquat desiccate plant tissue rapidly (Ahrens 1994), which likely reduced glyphosate translocation. Volunteer CFW control 14 DAT was 95 to 99% with paraquat + diuron; 61 to 88% with quizalofop-P, clethodim, and paraquat; and 38 to 55% with glufosinate at Moscow and Ralston in 2000 and 2001.

Control of volunteer CFW was 93 to 96% 21 DAT with all treatments, except glufosinate (46%), glyphosate-IPA + glufosinate (79%), paraquat (63%), and glyphosate-IPA + paraquat (66%).

Volunteer CFW biomass data were analyzed by individual locations and years because there was a significant location by year by treatment interaction ($P = 0.0028$) (data not shown). Volunteer CFW biomass was reduced 83 to 100% by all treatments, except glyphosate-IPA + glufosinate (60 to 82%) at Ralston, paraquat + diuron (78%) at Moscow in 2000, glyphosate-IPA + paraquat (53 to 82%), paraquat (66 to 84%), and glufosinate (45 to 78%) (Table 3). The large amount of variability biomass reduction between years and locations was the result of different levels of regrowth.

Volunteer CFW poses less of a challenge than volunteer RRW because it is easily controlled with glyphosate or tank mixes including glyphosate. However, paraquat + diuron usually controlled both volunteer CFW and RRW effectively and is an alternative in situations where growers do not want to use glyphosate.

Compared with CFW, RRW control was slightly less with paraquat + diuron 14 DAT ($P = 0.044$). By 21

DAT, paraquat + diuron controlled RRW and CFW equally well ($P = 0.249$). RRW and CFW control 14 and 21 DAT was not different with clethodim or quizalofop-P ($P = 0.623$ to 0.933).

Volunteer CFW control 21 DAT was similar with clethodim, quizalofop-P, and glyphosate alone (Table 2). However, at 14 DAT, CFW control averaged 72% with clethodim and quizalofop-P compared with 91% with glyphosate-IPA. In addition, control of volunteer RRW and CFW with clethodim and quizalofop-P varied 25 percentage points between locations and years, whereas control of CFW with glyphosate-IPA varied only 10 percentage points between locations and years. Rapid, effective kill of volunteer cereals is important to reduce the harmful effects of dying plants (green-bridge) (Cook and Veseth 1991). The longer time period required for volunteer wheat control to reach an acceptable level with quizalofop-P and clethodim will likely increase the time between herbicide application and the ideal seeding date to prevent disease and insect problems associated with the green-bridge. In addition, delayed seeding often reduces spring wheat yield potential (Blue et al. 1990; Ciha 1983; Dahlke et al. 1993; Shah et al. 1994; Young et al. 2003).

Another concern with clethodim, quizalofop-P, and other ACCase-inhibiting herbicides is that they can rapidly select for herbicide-resistant weed biotypes (Devine and Shimabukuro 1994). Growers who use conservation tillage systems rely heavily on ACCase inhibitors for weed control in wheat, barley, pea (*Pisum sativum* L.), lentil (*Lens culinaris* Medic.), and canola (*Brassica napus* L. and *Brassica rapa* L.) (Légère et al. 2000). Increased use of ACCase-inhibiting herbicides could result in more herbicide-resistant grass weed biotypes.

Clethodim and quizalofop-P have little to moderate soil residual activity (Ahrens 1994) and are registered for preplant burndown or fallow use. However, their registrations state that several crops including cereals should not be seeded until 30 and 120 d after application of clethodim and quizalofop-P, respectively (Anonymous 2004). Consequently, preplant applications of clethodim would further increase the time required between herbicide application and seeding, whereas quizalofop-P would only be feasible during long fallow periods. Little research has been conducted to assess the safety and effectiveness of graminicides as burndown herbicides before seeding wheat. In addition to being less effective than glyphosate, clethodim and quizalofop-P cost approximately twice as much (McGregor Company, personal communication) and require tank mixing with an additional herbicide for broadleaf weed control.

Paraquat + diuron consistently and adequately controlled CFW and RRW 14 and 21 DAT and, based on these studies, appears to be the best alternative to glyphosate for volunteer RRW control. However, the commercially premixed formulation of paraquat + diuron costs approximately $20 to 25/ha compared with $10 to 15/ha for glyphosate (McGregor Company, personal communication).

CFW will likely be widely adopted because volunteers can easily be controlled using glyphosate, but the acceptance of RRW will, in part, depend on the willingness of growers to use possibly less effective and more costly herbicides or tillage to control volunteer crops.

Glyphosate-Resistant Canola. Glyphosate alone, clethodim, and quizalofop-P did not control RRC, and data from these treatments were not included in the ANOVA for control 14 and 21 DAT. There was a significant treatment by year interaction for RRC control 14 DAT ($P < 0.0001$) and 21 DAT ($P < 0.0001$) because control with glyphosate/dicamba was 16 to 23% less 14 DAT and 21 to 35% less 21 DAT at both locations in 2001, compared with 2000 (data not shown). Although it is unclear exactly why control with glyphosate/dicamba was considerably less in 2000, one possibility is that plants were growing more rapidly at the time of application. However, all other treatments controlled volunteer RRC similarly between locations and years. Therefore, data were pooled over locations and years. RRC control 14 DAT was 92 to 97% with paraquat + diuron, glyphosate-IPA + paraquat, and paraquat (Table 4). All other treatments controlled volunteer RRC less than 78% 14 DAT. By 21 DAT, paraquat + diuron controlled RRC 98%, whereas control with other treatments ranged from 37 to 81%.

Volunteer RRC biomass was reduced 84 to 99% compared with the untreated control by paraquat + diuron, paraquat, glyphosate-IPA + paraquat, and glyphosate/2,4-D. Glyphosate/dicamba, glufosinate, and glyphosate-IPA + glufosinate reduced volunteer RRC biomass 29 to 71%. Biomass of volunteer RRW ranged from 75 to 113% of the untreated control in plots treated with glyphosate alone, glyphosate-IPA + clethodim, clethodim, glyphosate-IPA + quizalofop-P, and quizalofop-P.

Imidazolinone-Resistant Canola. Quizalofop-P and clethodim did not control volunteer CFC and were not included in the ANOVA for control 14 and 21 DAT. The location by treatment by year interaction was significant ($P < 0.0001$) for control 14 DAT because of 10 to 13 percentage points less control with glufosinate at Moscow in 2000 and Ralston in 2001 and 13 to 17 percent-

Table 4. The effect of herbicide treatment on volunteer glyphosate-, glufosinate-, and imidazolinone-resistant canola (RRC, LLC, and CFC, respectively) control 14 and 21 DAT and percent biomass 28 DAT. Data are pooled over locations and years.[a]

	Control						Biomass[b]		
	14 DAT			21 DAT			28 DAT		
Treatment	RRC	CFC	LLC	RRC	CFC	LLC	RRC	CFC	LLC
	% control						% of the control		
Glyphosate-IPA[c] + AMS[d,e]	—	95	94	—	96	94	91	5	5
Glyphosate/2,4-D[f] + AMS	78	96	95	81	98	98	9	3	3
Glyphosate/dicamba[g] + AMS	33	96	97	37	98	98	71	4	2
Paraquat + NIS[h]	92	93	95	76	70	73	12	35	31
Glufosinate	51	46	—	54	48	—	29	51	116
Glyphosate-DA[i] + AMS	—	92	92	—	94	95	75	7	14
Glyphosate-IPA + glufosinate + AMS	53	84	92	48	88	93	38	14	13
Glyphosate-IPA + paraquat + AMS + NIS	94	92	96	66	67	85	16	38	17
Paraquat + diuron + NIS	97	98	98	98	97	98	1	3	2
Quizalofop-P + NIS	—	—	—	—	—	—	112	113	95
Glyphosate-IPA + quizalofop-P + AMS + NIS	—	91	93	—	96	97	97	4	5
Clethodim + COC[j]	—	—	—	—	—	—	102	116	93
Glyphosate-IPA + clethodim + AMS + COC	—	94	95	—	95	96	113	5	7
LSD (0.05)	5	5	3	7	5	4	27	30	32

[a] Abbreviations: DAT, days after treatment; IPA, isopropylamine salt; AMS, ammonium sulfate; NIS, nonionic surfactant; DA, diammonium salt; COC, crop oil concentrate.

[b] Does not include 2000 Ralston, WA, canola data.

[c] Glyphosate isopropylamine salt, Roundup ULTRA™ RT (Monsanto Company).

[d] Five percent v/v is equivalent to 7.7 kg/378.5 L spray volume. Bronc Max (Wilbur-Ellis Company).

[e] Dashes indicate that the treatment was not included in data analysis because it did not control the volunteer crop.

[f] Applied as the commercial formulation Landmaster BW® (Monsanto Company).

[g] Applied as the commercial formulation Fallow Master® (Monsanto Company).

[h] R-11® (Wilbur-Ellis Company).

[i] Glyphosate diammonium salt, Touchdown® (Syngenta).

[j] Moract® (Wilbur-Ellis Company).

age points less control with glyphosate-IPA + quizalofop-P at Ralston in 2000, compared with other locations and years. Other treatments similarly controlled CFC 14 DAT; thus, data were pooled over locations and years. All treatments, except glufosinate (46%) and glyphosate-IPA + glufosinate (84%), controlled volunteer CFC 91 to 98% 14 DAT (Table 4).

There was a significant location by treatment by year interaction ($P < 0.0001$) for CFC control 21 DAT because control with paraquat was 50% at Moscow in 2000 (due to more regrowth), compared with 75 to 78% at other locations and years (data not shown). Other treatments were similar between locations and years; thus, data were pooled. By 21 DAT, CFC was controlled 94 to 98% by all treatments, except glyphosate-IPA + glufosinate (88%), glyphosate-IPA + paraquat (67%), glufosinate (48%), and paraquat (70%).

Volunteer CFC biomass was reduced 86 to 97% by paraquat + diuron and all treatments containing glyphosate, except glyphosate-IPA + paraquat (62%). Volunteer CFC biomass was not reduced by clethodim or quizalofop-P and was reduced only 49 and 65% by glufosinate and paraquat, respectively.

Glufosinate-Resistant Canola. Glufosinate, quizalofop-P, and clethodim did not control volunteer CFC and were not included in the ANOVA for control 14 and 21 DAT. The location by treatment by year interaction for LLC control 14 DAT was significant ($P < 0.0001$) because control was 3 to 9 percentage points less with glyphosate-IPA and glyphosate/2,4-D at Ralston in 2000 and Moscow in 2001, compared with other locations and years (data not shown). Control with other treatments was similar between locations and years, and data were pooled. LLC was controlled 92 to 98% by all treatments 14 DAT (Table 4).

Analysis of LLC control 21 DAT indicated a treatment by year interaction ($P < 0.0001$) because of 7 to 8% less control with glyphosate-IPA + paraquat at Moscow and Ralston in 2001 (data not shown). Control with other treatments was similar between locations and years; thus, data were pooled over locations and years. By 21 DAT, control ranged from 93 to 98% with all treatments, except paraquat (73%) and glyphosate-IPA + paraquat (85%). All treatments, except clethodim, quizalofop-P, and glufosinate, reduced volunteer LLC biomass 69 to 98%. Paraquat and paraquat + diuron controlled CFC, RRC, and LLC equally (97 to 98%) 14 and 21 DAT ($P = 0.089$ to 0.633).

Volunteer canola is a growing weed problem in major canola-producing regions of Canada (Simard et al. 2002). In a 1997 survey of Manitoba cereal and oilseed crops, volunteer canola was the 19th most common weed, and although there was not an increase in canola hectares, volunteer canola ranked 10th in 2002 (Van Acker et al. 2002). Volunteer herbicide-resistant canola should be controlled before planting canola because gene flow between canola cultivars with different resistance technologies can result in volunteer canola with resistance to multiple herbicides (Hall et al. 2000). The risk of hybridization with weedy relatives increases if volunteer herbicide-resistant canola is not controlled during fallow periods (Jørgenson and Anderson 1994). Hybridization of herbicide-resistant canola with weedy relatives likely will reduce the effectiveness of herbicide-resistant canola as a weed management tool.

Volunteer canola seed can persist in the soil up to 5 yr after a canola crop (Simard et al. 2002); consequently, it will be necessary to mix an effective broadleaf herbicide with glyphosate to control volunteer RRC in conservation tillage systems for many years. In this study, glyphosate/2,4-D only controlled volunteer RRC canola 81% 21 DAT. Other research has shown that auxinic herbicides do not always effectively control volunteer canola in spring cereals and that efficacy decreases as plants get larger (Simard and Légère 2002). Currently, paraquat + diuron appears to be the best alternative to glyphosate for control of volunteer herbicide-resistant canola.

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