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Alternative to Hand-Weeding Volunteer Potato (*Solanum tuberosum*) in Carrot (*Daucus carota*)[1]

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Abstract: Few herbicides are used in carrot production in the United States, and none suppress volunteer potato, a serious weed where the two crops are grown in rotation. Hand-weeding is the primary method of controlling emerged volunteer potato within carrot. The objective of this work was to evaluate carrot tolerance and volunteer potato control with single or sequential applications of prometryn, prometryn plus fluroxypyr, and ethofumesate. The treatment with fluroxypyr resulted in malformed carrots with numerous root hairs and reduced carrot yield. Treatments with prometryn, either as single or sequential POST applications at 2.23 kg ai/ha, were safe on carrot and frequently controlled volunteer potato similar to the hand-weeded treatment. Ethofumesate applied as single or sequential PRE or POST at 2.2 kg ai/ha proved safe on carrot, but higher rates reduced yield. Ethofumesate applied POST or PRE followed by POST consistently reduced volunteer potato tuber mass. If registered for use in carrot, prometryn and ethofumesate would help modernize weed management in carrot and reduce or eliminate the need for hand-weeding volunteer potato.

Nomenclature: ethofumesate; fluroxypyr; prometryn; potato, *Solanum tuberosum* L.; carrot, *Daucus carota* L.

Additional index words: Crop injury, integrated weed management, minor crop, tuber density, vegetable.

Abbreviations: EPOST, early postemergence; LPOST, late-postemergence; MPOST, midpostemergence.

INTRODUCTION

Fresh and processed carrots are the primary source of vitamin A in the American diet. Carrot production in the United States has risen by 125% in the last decade and was recently valued at $665 million (Anonymous 2004). Carrots are grown on 44,880 ha in the Western and Midwest regions of the United States and account for more than 85% of commercial carrot production (Anonymous 2004).

Carrot is a small-seeded, slow-growing crop subject to yield losses from weed competition. Weeds reduce yield and quality of carrot and add significant cost to production. Volunteer potato is the most troublesome weed when potato is grown in rotation with carrot because weed control methods are very limited. Volunteer potato is also a host to insects, diseases, and nematodes of potato, including early and late blight and corky ringspot (Mojtahedi et al. 2003).

Soil fumigation, cultivation, and hand-weeding are important practices for controlling volunteer potato in carrot. Fumigation with rates as low as 41 kg ai/ha of 1,3-dichloropropene or 96 kg ai/ha of metham sodium reduce potato tuber viability (Boydston and Williams 2003). The high crop density in carrot production limits the use of mechanical cultivation for control of in-row weeds. No suitable herbicides are registered for control of volunteer potato in carrot in the United States. Metoxuron has been used in Europe but with limited success (Lutman 1974; Orson 1990). Hand-weeding is the principal method employed POST to control volunteer potato.

Prometryn, fluroxypyr, and ethofumesate were found to be phytotoxic to potato and are being evaluated for volunteer potato control in carrot. Prometryn is registered for use in cotton (*Gossypium hirsutum* L), celery (*Apium graveolens* L.), pigeon peas (*Cajanus cajan* L.), and carrot for seed. Fluroxypyr is registered for volunteer potato control in small grains, fallow, and for emergency use in sweet corn (*Zea mays* L.) and field corn in the Pacific Northwest. Ethofumesate is registered for use

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in sugarbeet (*Beta vulgaris* L.) and grass seed production for control of annual grass and broadleaf weeds. A previous study indicated ethofumesate suppressed volunteer potato (C. Stanger, personal communication).

The objective of this work was to evaluate carrot tolerance and volunteer potato control with single or sequential applications of prometryn, prometryn plus fluroxypyr, and ethofumesate.

MATERIALS AND METHODS

Prometryn Study. Trials were conducted in 2002 and 2003 in carrot grown near Alderdale, WA, on a Quincy sand (mixed, mesic Xeric Torripsamments). Volunteer potato was present from natural populations that developed from a previous potato crop; var. 'Ranger Russet' in 2001 and var. 'Umatilla' in 2002 for the 2002 and 2003 sites, respectively. 'Enterprise' carrot was planted on June 27, 2002, and May 27, 2003, at 1,853,000 seed/ha. Planting arrangement was two sets of three lines, spaced 10-cm apart, on raised beds measuring 56 cm across the top and 1.0 m between furrows. Carrot was grown under sprinkler irrigation and standard production practices (Sorensen 2000). Broadcast herbicide treatments included preplant application of glyphosate at 1.1 kg ae/ha and a PRE application of linuron at 0.6 kg ai/ha.

Plots measured 2.0 by 9.1 m and were replicated three times (2002) and four times (2003) in a randomized complete block design. Herbicides were applied with a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles and operated at a pressure of 172 kPa in a total volume of 252 L/ha. Prometryn was evaluated at 1.12 kg ai/ha applied twice, 2.23 kg/ha applied once with or without an adjuvant[3] at 0.5% (v/v), or 2.23 kg/ha applied once with fluroxypyr at 140 g ae/ha and no adjuvant. A hand-weeded treatment and nontreated control were included for comparison. Emerged volunteer potato shoots were removed every 2 wk in the hand-weeded treatment from the time of midpostemergence (MPOST) through the remainder of the experiment. Herbicides were applied MPOST and late-postemergence (LPOST) when carrot had four and six leaves, respectively. MPOST were applied July 31, 2002, and July 1, 2003, and LPOST were applied August 13, 2002, and July 15, 2003. Most volunteer potato shoots had 8 to 10 leaves with 2- to 3-cm long tubers forming at the time of MPOST applications both years.

Carrot and volunteer potato were rated visually 1 wk after LPOST applications for stunting, leaf necrosis, and epinastic growth as a percentage of the nontreated control. Volunteer potato plant density was determined throughout nontreated potato-only plots before carrot harvest. Carrot was hand-harvested on October 17, 2002, and October 1, 2003. Carrot was harvested from the center 1.0 m of each plot, to a length of 6.1 m, topped, counted, and weighed. Immediately after carrot harvest, the top 25 cm of soil was sifted by hand to recover potato tubers, which were counted and weighed.

Data from both years were combined, tested for homogeneity of variance and subjected to ANOVA. Treatment means were separated by Fisher's protected LSD at $P = 0.05$ level. Statistical tests were performed using SAS.[4]

Ethofumesate Study. Trials were conducted in 1996 and 2003 near Prosser, WA, on a Warden silt loam (coarse-silty, mixed, superactive, mesic Xeric Haplocambids). Whole seed (65 g) potato tubers, var. 'Russet Burbank', were planted on March 29, 1996, and April 8, 2003, to simulate volunteer potatoes. Potatoes were planted in rows spaced 86-cm apart at 10-cm depth. 'Cosmos' carrot was planted on April 5, 1996, and April 18, 2003, in single rows spaced 56-cm apart to obtain a final plant population of 230,000 and 159,000 plants/ha in 1996 and 2003, respectively. Carrot was grown as described above.

Plots measured 2.8 m (1996) or 2.2 m (2003) by 9.1 m and replicated three times (1996) and four times (2003) in a randomized complete block design. Herbicides were applied with a CO_2-pressurized bicycle sprayer equipped with flat-fan nozzles and operated at a pressure of 185 kPa in a total volume of 187 L/ha. Ethofumesate was tested at rates of 1.7 and 3.4 kg ai/ha applied PRE, with both treatments followed by 2.2 kg/ha of ethofumesate applied early postemergence (EPOST). Ethofumesate was also tested at 4.4 kg/ha applied once at EPOST or as 2.2 kg/ha applied sequentially at EPOST and LPOST, with both treatments preceded by linuron applied PRE at 0.6 kg/ha. Pendimethalin applied PRE at 0.6 kg ai/ha followed by linuron applied EPOST at 1.1 kg/ha was included. A hand-weeded treatment was added in 2003. Herbicides were applied PRE on April 10, 1996, and April 29, 2003. Herbicides were applied EPOST and LPOST when carrot was at the two- and six-leaf stage, respectively. EPOST were applied May 17, 1996, and May 21, 2003, and LPOST were applied

[3] X-77® spreader (alkylarylpolyoxyethylene glycols-free fatty acids, isopropanol), Loveland Industries, Inc., P.O. Box 1289, Greeley, CO 80632.

[4] SAS, v. 8.01. Statistical Analysis Systems Institute, Inc., SAS Circle, Box 8000, Cary, NC 25712-8000.

Table 1. Volunteer potato control and number and mass of tubers at carrot harvest after postemergence applications of prometryn and fluroxypyr in 2002 and 2003 near Alderdale, WA.[a]

Treatment	Timing[b,c]	Rate	Potato control[d]		Number of tubers		Mass of tubers	
			2002	2003	2002	2003	2002	2003
		kg/ha	%		% of nontreated check			
Prometryn	MPOST + LPOST	1.12 + 1.12	77	69	19	34	6	8
Prometryn	MPOST	2.23	42	86	16	14	12	3
Prometryn + adjuvant[e]	MPOST	2.23	63	90	4	26	8	6
Prometryn + fluroxypyr	MPOST	2.23 + 0.14	58	74	5	19	2	10
Nontreated potato-only[f]			0	0	—	—	—	—
Hand-weeded			100	100	0	5	0	6
LSD (0.05)			14	13	20	21	14	6

[a] Data from 2002 and 2003 were not combined because of a significant treatment by year interaction.
[b] Abbreviations: MPOST, midpostemergence; LPOST, late-postemergence.
[c] MPOST applied on July 31, 2002, and July 1, 2003; LPOST applied on August 13, 2002, and July 15, 2003.
[d] Volunteer potato control was visually estimated 1 wk after LPOST applications.
[e] X-77® spreader applied at 0.5% v/v.
[f] Nontreated potato-only checks contained 8.3 and 12.5 tubers/m^2 weighing 402 and 1,135 g in 2002 and 2003, respectively.

June 19, 1996, and June 16, 2003. Most volunteer potato shoots had six leaves and were beginning to initiate tubers. Carrot was cultivated with a tractor-mounted cultivator in 1996 and by hand hoeing in 2003 at 10 d following POST treatments to remove all potato shoots between the carrot rows. Potato shoots within 6 cm of the carrot row were not removed either year and averaged 1.6 and 2.4 plants/m^2 following cultivation in 1996 and 2003, respectively.

Carrot and volunteer potato were rated visually 3 wk after LPOST applications in 1996, and 2 wk after LPOST applications in 2003, for stunting, leaf chlorosis, and epinastic growth as a percentage of the control. Crop stand counts were taken over 12.2 m of row per plot on May 13, 1996, and May 21, 2003. Carrot was harvested by hand August 7, 1996, and August 4, 2003. All carrots were removed from the center two rows of each plot, to a length of 6.1 m, topped, and weighed. On the day of harvest in 1996 and August 18, 2003, the top 25 cm of soil was sifted by hand to recover potato tubers, which were counted and weighed.

Data from both years were combined, tested for homogeneity of variance, and subjected to ANOVA. When ANOVA were significant, treatment means were separated by Fisher's protected LSD at $P = 0.05$ level.

RESULTS AND DISCUSSION

Prometryn Study. Volunteer potato density in nontreated potato-only plots averaged 1.4 plants/m^2 in 2002 and 2.7 plants/m^2 in 2003. Newberry and Thornton (1999) reported up to 10.1 volunteer potato plants/m^2 based on emergence surveys conducted in the spring. Populations at the experimental site were possibly higher than the densities observed at the time of treatment application but were reduced by soil fumigation, preplant application of glyphosate, and preplant tillage. Nontreated volunteer potato produced 8.3 and 12.5 tubers/m^2 in 2002 and 2003, respectively.

Prometryn applied POST initially caused chlorosis to potato leaf margins followed by necrotic lesions and stunted growth within one week of application. Fluroxypyr with prometryn caused cupped leaves and epinastic growth on potato foliage. There was a significant year by treatment effect, so data from each year were analyzed separately. All prometryn treatments provided potato control 1 wk after LPOST. In 2002, the most effective treatments were the sequential applications of prometryn and prometryn plus adjuvant (Table 1). In 2003, all prometryn treatments were comparable to or exceeded the highest level of control from the previous year, with prometryn plus adjuvant being comparable to the hand-weeded treatment.

All prometryn treatments reduced volunteer potato tuber production. Prometryn reduced number of potato tubers by 66% or more (Table 1). Mass of potato tubers was reduced by prometryn to the same level as the hand-weeded treatment, ranging from 2 to 12% of the nontreated control (Table 1). The few tubers found in the hand-weeded treatment resulted from volunteer potato reemerging after shoot-removal events (Williams and Boydston 2002).

Carrot yield in the hand-weeded treatment averaged 87.5 and 84.4 Mg/ha in 2002 and 2003, respectively (Table 2). Nontreated volunteer potato reduced carrot yield 34% in 2003, but no yield reduction was observed in 2002. Carrot tolerated volunteer potato competition at

Table 2. Carrot injury and yield after postemergence applications of prometryn and fluroxypyr in 2002 and 2003 near Alderdale, WA.[a]

Treatment	Timing[b,c]	Rate	Carrot injury[d]		Carot number		Mass of carrot	
			2002	2003	2002	2003	2002	2003
		kg/ha	%		no./m²		Mg/ha	
Prometryn	MPOST + LPOST	1.12 + 1.12	7	3	95	74	82.6	75.5
Prometryn	MPOST	2.23	7	4	86	76	81.6	73.8
Prometryn + adjuvant[e]	MPOST	2.23	7	6	95	76	78.9	78.0
Prometryn + fluroxypyr	MPOST	2.23 + 0.14	23	16	103	70	76.2	75.4
Nontreated potato-only			0	0	91	78	88.0	55.7
Hand-weeded			0	0	85	89	87.5	84.4
LSD			9	5	20	20	9.4	10.1

[a] Data from 2002 and 2003 were not combined because of a significant treatment by year interaction.
[b] Abbreviations: MPOST, midpostemergence; LPOST, late-postemergence.
[c] MPOST applied on July 31, 2002, and July 1, 2003; LPOST applied on August 13, 2002, and July 15, 2003.
[d] Carrot injury was visually estimated 1 wk after LPOST applications.
[e] X-77® spreader applied at 0.5% v/v.

1.4 potato plants/m². Boydston and Seymour (1996) observed a 27% yield reduction because of volunteer potato with densities of 4.8 plants/m². Our results confirm that carrot yield is susceptible to losses in the presence of volunteer potato, but additional research should quantify functional relationships between carrot yield and weed density.

Few injury symptoms were observed on carrot treated POST with prometryn alone except for minor leaf-margin necrosis and temporary stunting within a week of herbicide application. Carrot injury 1 wk after LPOST was 7% or less for all prometryn-alone treatments (Table 2). Addition of fluroxypyr resulted in moderate epinasty to carrot foliage, with 23 and 16% injury in 2002 and 2003, respectively. Herbicide treatments did not appear to reduce carrot number at harvest. Prometryn with fluroxypyr is unlikely to be a viable alternative to hand-weeding in carrot. Carrot yield was reduced 14% compared with the nontreated control in 2002. Fluroxypyr treatments had no aboveground symptoms at harvest, but abnormally large and numerous root hairs were observed resulting in a nonmarketable crop (T. Crosby, personal communication). In contrast, prometryn alone was considerably safer on carrot. Carrot yield was similar to hand-weeded when prometryn was applied MPOST and LPOST at 1.12 kg/ha or MPOST at 2.23 kg/ha plus adjuvant. Kuratle and Rahn (1968) found that two-leaf carrot could tolerate up to 5.6 kg/ha of prometryn and that prometryn often caused less crop injury than linuron, an herbicide used in carrot production.

Ethofumesate Study. POST applications of ethofumesate crinkled potato leaves and caused epinastic foliage. Pendimethalin applied PRE did not injure potato and is registered for weed control in potato. Linuron applied POST caused temporary chlorosis on potato foliage for several wks. Preemergence applications of ethofumesate at 1.7 and 3.4 kg/ha delayed potato emergence in late April and early May compared with treatments in which no ethofumesate was applied PRE (personal observation).

A combined ANOVA of injury rating data indicated a year effect; therefore, data were analyzed by year. All ethofumesate treatments provided volunteer potato control shortly after herbicide application. Weed control 3 wks after LPOST in 1996 was greatest (82 to 83%) with ethofumesate applied POST as two sequential applications of 2.2 kg/ha or one application at 4.4 kg/ha (Table 3). Ethofumesate applied PRE followed by ethofumesate POST controlled potato 43 to 50%. Volunteer potato control at 2 wk after LPOST in 2003 was similar among all ethofumesate treatments, ranging from 80 to 90% (Table 3). Unexpectedly, volunteer potato was partially controlled (70%) by linuron in 2003, which may have been more of a function of arthropod herbivory than linuron application. A large population of Colorado potato beetle (*Leptinotarsa decemlineata* Say) moved into the experimental area and completely defoliated volunteer potato in two of the four replications by the time of herbicide ratings. Williams et al. (2004) reported the ability of Colorado potato beetle to significantly reduce volunteer potato growth and fitness, particularly when the weed is stressed by sublethal doses of herbicide.

Nontreated volunteer potato produced 16 and 30 tubers/m² in 1996 and 2003, respectively. Compared with the pendimethalin/linuron treatment, none of the ethofumesate treatments significantly reduced the number of potato tubers produced either year (Table 3). Treatments with preemergence applications of ethofumesate reduced tuber number 28 to 45% compared with the nontreated potato-only treatment in 2003 (Table 3). Ethofumesate

Table 3. Volunteer potato control and number and mass of tubers at carrot harvest after treatment with ethofumesate in 1996 and 2003 near Prosser, WA.[a]

Treatment	Timing[b,c]	Rate	Poato control[d] 1996	Poato control[d] 2003	Number of tubers 1996	Number of tubers 2003	Mass of tubers 1996	Mass of tubers 2003
		kg/ha	%	%	% of check[e]	% of check[e]	% of check[e]	% of check[e]
Ethofumesate	PRE + EPOST	1.7 + 2.2	50	82	96	45	59	21
Ethofumesate	PRE + EPOST	3.4 + 2.2	43	90	75	28	52	7
Pendimethalin	PRE	0.6	82	80	113	65	48	54
Ethofumesate	EPOST + LPOST	2.2 + 2.2						
Pendimethalin	PRE	0.6	83	86	123	72	35	38
Ethofumesate	EPOST	4.4						
Pendimethalin	PRE	0.6	0	70	100	33	100	35
Linuron (1996 check)	EPOST	1.1						
Nontreated weedy			0	—	87	—	15	—
Nontreated potato-only (2003 check)			—	0	—	100	—	100
Hand-weeded			—	100	—	0	—	0
LSD			16	21	42	40	24	45

[a] Data from 1996 and 2003 were not combined because of a significant treatment by year interaction and alterations in treatments tested.

[b] Abbreviations: PRE, preemergence; EPOST, early postemergence; LPOST, late-postemergence.

[c] PRE applied on April 10, 1996, and April 29, 2003; EPOST applied on May 17, 1996, and May 21, 2003; and LPOST applied on June 19, 1996, and June 16, 2003.

[d] Potato control was visually estimated 3 and 2 wks after LPOST applications in 1996 and 2003, respectively.

[e] Check used for comparison in 1996 was pendimethalin/linuron standard treatment. Check used for comparison in 2003 was the nontreated potato-only treatment.

[f] Pendimethalin/linuron treatment (check) in 1996 contained 16 tubers/m^2 weighing 1,840 g. Nontreated potato-only checks in 2003 contained 30 tubers/m^2 weighing 1,011 g.

applied PRE at 3.4 kg/ha followed by ethofumesate applied EPOST at 2.2 kg/ha was comparable to the hand-weeded treatment. Tuber number was variable in 2003 because of severe defoliation from Colorado potato beetle. The inclusion of ethofumesate in mixtures with either phenmedipham or metamitron gave additional suppression of volunteer potato foliage and a reduction in the number of tubers produced in sugarbeet (May and Hilton 1993).

In 1996, all ethofumesate treatments reduced tuber mass compared with the pendimethalin/linuron treatment. PRE ethofumesate followed by POST ethofumesate reduced tuber weight by 41 to 48% compared with the pendimethalin/linuron treatment (Table 3). Two sequential POST applications of ethofumesate reduced tuber weight by 52% and ethofumesate applied POST once at 4.4 kg/ha reduced tuber weight 65% compared with the pendimethalin/linuron treatment. Uncontrolled common lambsquarters (*Chenopodium album* L.), redroot pigweed (*Amaranthus retroflexus* L.), and barnyardgrass (*Echinochloa crus-galli* L.) in the nontreated weedy checks, reduced potato tuber weight 85% compared with the pendimethalin/linuron treatment in 1996.

Tuber mass was variable in 2003 because of Colorado potato beetle discussed previously, but all treatments reduced tuber mass. Herbicide treatments reduced tuber mass 46 to 93% compared with nontreated potato-only (Table 3). Ethofumesate applied PRE at 3.4 kg/ha followed by ethofumesate applied POST at 2.2 kg/ha reduced tuber mass significantly more than two sequential POST applications of ethofumesate at 2.2 kg/ha.

Ethofumesate applied PRE or POST occasionally caused fused carrot leaves and malformed growth, but carrot stand counts were not affected (data not shown). Carrot was injured most (12 to 20%) by sequential applications of ethofumesate applied PRE at 3.4 kg/ha followed by ethofumesate applied POST at 2.2 kg/ha (Table 4). Carrot response was least (3 to 6%) and similar to the pendimethalin/linuron treatment when ethofumesate was POST-applied sequentially at 2.2 kg/ha.

Carrot yield in the pendimethalin/linuron treatment averaged 22.9 and 22.3 Mg/ha in 1996 and 2003, respectively (Table 4). All weeds left nontreated reduced carrot yield by 99% in 1996. Volunteer potato alone resulted in 15% less carrot yield in 2003, but not different than the hand-weeded treatment. Most ethofumesate treatments resulted in carrot yields comparable to the pendimethalin/linuron treatment, despite the lack of volunteer potato control in the latter. One exception was ethofumesate applied PRE at 3.4 kg/ha plus EPOST at 2.2 kg/ha, where yields were reduced 26 to 33%. The similar yield among herbicide treatments differing in volunteer potato control could be due to several factors including (1) ethofumesate injury to carrot offset any yield gains from volunteer potato control, (2) cultivation and late-season Colorado potato beetle herbivory diminished the effects of volunteer potato competition with

Table 4. Carrot injury and yield after treatment with ethofumesate in 1996 and 2003 near Prosser, WA.[a]

Treatment	Timing[b,c]	Rate	Carrot injury[d]		Mass of carrot	
			1996	2003	1996	2003
		kg/ha	%		Mg/ha	
Ethofumesate	PRE + EPOST	1.7 + 2.2	7	10	20.6	21.0
Ethofumesate	PRE + EPOST	3.4 + 2.2	12	20	17.0	14.9
Pendimethalin	PRE	0.6	6	3	25.1	22.1
Ethofumesate	EPOST + LPOST	2.2 + 2.2				
Pendimethalin	PRE	0.6	11	7	21.2	21.5
Ethofumesate	EPOST	4.4				
Pendimethalin	PRE	0.6	0	0	22.9	22.3
Linuron	EPOST	1.1				
Nontreated weedy			0	—	0.2	—
Nontreated potato-only			—	0	—	18.1
Hand-weeded			—	0	—	21.4
LSD			7	4	4.8	4.2

[a] Data from 1996 and 2003 were not combined because of a significant treatment by year interaction and alteration in treatments tested.

[b] Abbreviations: PRE, preemergence; EPOST, early postemergence; LPOST, late-postemergence.

[c] PRE applied on April 10, 1996, and April 29, 2003; EPOST applied on May 17, 1996, and May 21, 2003; and LPOST applied on June 19, 1996, and June 16, 2003.

[d] Carrot injury was visually estimated 3 and 2 wks after LPOST applications in 1996 and 2003, respectively.

carrot, and (3) volunteer potato density remaining after cultivation was insufficient to impact carrot yield.

Carrot is not immune to injury from ethofumesate and prometryn but has considerable tolerance. Given the significant cost of hand-weeding, a limited amount of herbicide injury may be acceptable given the level of volunteer potato control these two herbicides provide. Ethofumesate applied PRE followed by prometryn applied POST warrants study. Both herbicides offer benefits to integrated weed management systems in carrot, particularly where volunteer potato is problematic.

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