Weed Technology

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Carrot weed management programs without linuron herbicide

Jed B. Colquhoun[1], Richard A. Rittmeyer[2] and Daniel J. Heider[3]

[1]Professor, Department of Horticulture, University of Wisconsin–Madison, Madison, WI, USA; [2]Senior Research Specialist, Department of Horticulture, University of Wisconsin–Madison, Madison, WI, USA and [3]Distinguished Outreach Specialist, Department of Horticulture, University of Wisconsin–Madison, Madison, WI, USA

Research Article

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Author for correspondence: Jed B. Colquhoun, Email: colquhoun@wisc.edu

Abstract

Linuron herbicide has been a mainstay of carrot weed management for years, but uncertainty around regulatory registration review and an increased prevalence of herbicide-resistant weeds have spurred interest in identifying alternatives that can be readily adopted in production. With this context in mind, herbicide programs were evaluated on a coarse-textured, low organic matter soil in 2015 and 2016. Season-long weed control without compromising yield was possible with weed management programs that included prometryn POST instead of linuron. With that said, a PRE herbicide such as pendimethalin was critical to establish an early-season competitive advantage for carrot plants over weeds, and careful attention should be paid to the prometryn rate, as selectivity is marginal. Carrot is often interseeded with a grain nurse crop to mitigate risk of wind erosion. Nurse crop injury was minimal where *S*-metolachlor, pendimethalin, or prometryn was applied at rates labeled for PRE use in carrot, with the exception of where prometryn was applied at rates above 1.1 kg ai ha^{-1}.

Introduction

Weed interference remains one of the greatest challenges in carrot production despite advances in integrated control strategies. In fact, Van Heemst (1985) reported that carrot was the most sensitive crop to weed interference of the 26 crops included in a global literature review. This sensitivity is largely related to inherent crop growth characteristics that include slow and variable crop emergence, relatively poor seedling vigor, and slow early-season canopy development (Colquhoun et al. 2017).

Weed interference in carrot reduces overall root yield, decreases quality by stimulating misshapen root development, and hinders mechanical harvest. Weed species spectrum varies by production region, but most often includes common annual broadleaf and grass species that emerge after preplant tillage. Marketable carrot root yield loss from season-long weed competition is often greater than 90% (Bellinder et al. 1997; Coelho et al. 2009; Freitas et al. 2009).

Linuron has been the mainstay of carrot herbicides for many years. Linuron is applied to carrot before or after emergence and controls several annual grass and broadleaf weeds, including some species when newly emerged. Many studies have demonstrated the broad utility of linuron in carrot crops. For example, carrot yield in weedy plots without herbicide was often 15% or less than where linuron was applied (Henne and Guest 1973; Henne and Poulson 1980). Bell et al. (2000) also reported carrot yield being about 6 times greater where linuron was applied PRE, POST, or at both timings compared with weedy carrot. In 2 study years, net profit where linuron was applied ranged from $980 to $6,426 ha^{-1} compared with $740 to $2,852 ha^{-1} where the carrot crop was hand weeded.

This long-standing backbone of the carrot weed management program has been compromised recently by use limitations and resistant weed selection. Linuron use is restricted on coarse-textured, low organic matter soils to mitigate crop injury and groundwater contamination risk. In 2017, the European Commission did not renew the approval of linuron for use in the European Union (European Commission 2018). Linuron is also under review as part of the regular pesticide registration review process conducted at least every 15 yr at the U.S. Environmental Protection Agency (USEPA 2018). Additionally, limited populations of several weed species common in carrot, such as redroot pigweed (*Amaranthus retroflexus* L.) and common lambsquarters (*Chenopodium album* L.), have been identified with linuron resistance (Heap 2018). With these limitations in mind, our goal here was to identify alternatives to linuron that could be readily adopted by carrot growers without compromising weed control or crop yield and quality.

Materials and methods

Studies were conducted in the 2015 and 2016 growing seasons on a mineral soil at the University of Wisconsin Hancock Agricultural Research. The soil type was a Plainfield loamy sand (mixed,

Table 1. Herbicide sources for carrot weed management studies in Hancock, WI, in 2015 and 2016.

Herbicide	Trade name	Manufacturer	Location
Ethofumesate	Ethotron™ SC	UPI	King of Prussia, PA
Linuron	Lorox® DF	NovaSource	Phoenix, AZ
Pendimethalin	Prowl® H_2O	BASF Corporation	Research Triangle Park, NC
Prometryn	Vegetable Pro®	MANA, Inc.	Raleigh, NC
S-metolachlor	Dual Magnum®	Syngenta Crop Protection, Inc.	Greensboro, NC

Table 2. Soil and climatic conditions at the time of PRE and 3- and 5-leaf carrot growth stage herbicide applications in Hancock, WI, in 2015 and 2016.

	2015			2016		
	PRE	3-leaf	5-leaf	PRE	3-leaf	5-leaf
Date	May 8	June 11	June 23	May 11	June 14	June 21
Time	12:00 PM	8:00 AM	9:00 AM	10:15 AM	8:30 AM	8:00 AM
Soil moisture, surface	Dry	Moist	Moist	Wet	Moist	Dry
Soil moisture, 2.5 cm	Moist	Moist	Moist	Wet	Moist	Dry
Soil temperature (C), surface	26	18	25	26	22	26
Soil temperature (C), 7.5 cm	22	19	21	19	19	22
Air temperature (C)	21	18	19	11	18	21
Wind (kg h^{-1}, direction)	6–13, W	3–8, NE	3–9, NW	3–8, E	3–8, E	3–10, W
Relative humidity (%)	73	69	75	84	74	68
Cloud cover (%)	75	100	10	100	90	10

mesic, Typic Udipsamments) with 0.8% organic matter and a pH of 6.5. Soil moisture was monitored, and supplemental irrigation was delivered through a pivot system, as is standard commercial practice in that region.

Individual plots measured 1.8-m wide by 6.1-m long and included three rows of ‘Enterprise’ carrot seeded at 70 seed m^{-1} of row. The studies were arranged in a randomized complete block design with four replications of each herbicide program. The studies were seeded on May 7, 2015, and May 10, 2016. Oat (*Avena sativa* L.) was seeded in three rows between the carrot rows at the same time as carrot seeding to mitigate risk of wind erosion and terminated before tillering with an application of clethodim, as is the industry norm in the area.

Herbicides were applied with a backpack air-pressure sprayer calibrated to deliver 187 L ha^{-1} at 186 kPa with TeeJet® XR8003VS nozzle tips (Spraying Systems, P.O. Box 7900, Wheaton, IL 60187) (Table 1). Pendimethalin (1.1 kg ai ha^{-1}), *S*-metolachlor (0.7 kg ai ha^{-1}), or ethofumesate (1.5 kg ai ha^{-1}) were applied PRE, followed by either prometryn (1.1 kg ai ha^{-1}), *S*-metolachlor (1.1 kg ai ha^{-1}), or ethofumesate (2.0 kg ai ha^{-1}) applied at the 3- and 5-leaf carrot growth stage. All programs included herbicides applied PRE and at the 3- and 5-leaf carrot growth stage. Nonionic surfactant (0.5% v/v) was included where prometryn was applied. Soil and climatic data were collected at the time of application (Table 2). All other production practices, including fertilizer and maintenance insecticide applications, followed typical commercial practices (Colquhoun et al. 2018). Carrot injury and weed control by species were visibly estimated on a scale of 0% (no injury) to 100% (plant death). Carrot roots were harvested at maturity, counted, and weighed. Harvest was conducted on September 22, 2015, and October 4, 2016. The studies were analyzed independently given a treatment by year interaction. Treatment data were subjected to ANOVA using the PROC GLM procedure in SAS (v. 9.4, SAS Institute, Cary, NC 27513). Data complied with ANOVA requirements related to homogeneity of variety and residual normality. Means were separated using Fisher’s protected LSD at P = 0.05.

Results and discussion

Weed control

In 2015, common lambsquarters control was particularly poor (55% to 78%) where *S*-metolachlor or ethofumesate was applied PRE. In contrast common lambsquarters control was nearly complete, ranging from 89% to 99%, where pendimethalin was applied PRE. Common lambsquarters control remained poor when evaluated at 78 d after seeding (DAS) where ethofumesate was applied PRE. Redroot pigweed control was reduced where *S*-metolachlor was applied at the 5-leaf carrot growth stage compared with where prometryn was applied at the same timing. Despite prolonged emergence throughout much of the season, common purslane (*Portulaca oleracea* L.) was completely controlled by all management programs (Table 3). In general, redroot pigweed control was better in 2016 than in 2015 (Table 4). Common lambsquarters control was minimal where *S*-metolachlor was applied PRE and reduced when ethofumesate was applied at the same timing compared with pendimethalin. By 63 DAS, common lambsquarters, redroot pigweed, and common purslane control was complete (100%; unpublished data). Redroot pigweed and common purslane control was 97% or better at both evaluation timings. At 78 DAS, common lambsquarters control was lowest where *S*-metolachlor was applied PRE.

Carrot injury

In 2015, carrot injury was minimal, except where *S*-metolachlor was applied PRE and ethofumesate was applied POST (Table 5). By 78 DAS, carrot plants had recovered and no injury was observed. In rotational crops such as potato (*Solanum tuberosum* L.), temporary injury is sometimes observed in association with early-season *S*-metolachlor applications, when climatic conditions are often cool and wet (Colquhoun et al. 2018). In 2016, carrot injury was observed in more weed management programs but never exceeded 13% (Table 6). Interestingly, weed control was also better in 2016

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Table 3. Visible estimation of weed control in carrot grown on coarse-textured, low organic matter soil in Hancock, WI, in 2015.[a]

Program[b]	Herbicide rate	63 DAS[c]			78 DAS		
		Common lambsquarters	Redroot pigweed	Common purslane	Common lambsquarters	Redroot pigweed	Common purslane
	kg ai ha−1	% control					
Pendimethalin fb prometryn fb prometryn	1.1 fb 1.1 fb 1.1	97	99 a	100	90	95	100
S-metolachlor fb prometryn fb prometryn	0.7 fb 1.1 fb 1.1	78	100 a	100	87	88	100
Pendimethalin fb prometryn fb *S*-metolachlor	1.1 fb 1.1 fb 1.1	94	89 b	100	82	87	100
Ethofumesate fb prometryn fb prometryn	1.5 fb 1.1 fb 1.1	55	100 a	100	57	98	100
Pendimethalin fb ethofumesate fb prometryn	1.1 fb 2 fb 1.1	99	100 a	100	90	100	100
Pendimethalin fb *S*-metolachlor fb prometryn	1.1 fb 1.1 fb 1.1	89	99 a	100	82	100	100

[a]Abbreviations: DAS, d after seeding; fb, followed by.
[b]Three herbicide applications were included in each program: PRE fb POST at 3-carrot leaf growth stage fb POST at 5-carrot leaf growth stage. All prometryn applications included nonionic surfactant applied at 0.5% v/v.
[c]Means followed by the same letter are not different according to Fisher's protected LSD test at P = 0.05. If no letters are included for a column, then no statistical differences were noted.

Table 4. Visible estimation of weed control in carrot grown on coarse-textured, low organic matter soil in Hancock, WI, in 2016.[a]

Program[b]	Herbicide rate	35 DAS[c]			78 DAS		
		Common lambsquarters	Redroot pigweed	Common purslane	Common lambsquarters	Redroot pigweed	Common purslane
	kg ai ha−1	% control					
Pendimethalin fb prometryn fb prometryn	1.1 fb 1.1 fb 1.1	100 a	100	100	100	100	100
S-metolachlor fb prometryn fb prometryn	0.7 fb 1.1 fb 1.1	9 c	100	100	83	100	98
Pendimethalin fb prometryn fb *S*-metolachlor	1.1 fb 1.1 fb 1.1	99 a	100	100	99	100	100
Ethofumesate fb prometryn fb prometryn	1.5 fb 1.1 fb 1.1	72 b	100	100	99	100	100
Pendimethalin fb ethofumesate fb prometryn	1.1 fb 2 fb 1.1	99 a	100	100	100	100	100
Pendimethalin fb *S*-metolachlor fb prometryn	1.1 fb 1.1 fb 1.1	99 a	100	100	100	100	100

[a]Abbreviations: DAS, d after seeding; fb, followed by.
[b]Three herbicide applications were included in each program: PRE fb POST at 3-carrot leaf growth stage fb POST at 5-carrot leaf growth stage. All prometryn applications included nonionic surfactant applied at 0.5% v/v.
[c]Means followed by the same letter are not different according to Fisher's protected LSD test at P = 0.05. If no letters are included for a column, then no statistical differences were noted.

Table 5. Visible estimation of carrot injury and carrot root yield grown on coarse-textured, low organic matter soil in Hancock, WI, in 2015.[a]

Program[b]	Herbicide rate	Injury		Carrot root	
		63 DAS	78 DAS	Number	Yield
	kg ai ha^{-1}	%		plant ha^{-1}	kg ha^{-1}
Nontreated	–	0	0	739,703	15,091
Hand weeded	–	0	0	767,498	71,804
Pendimethalin fb prometryn fb prometryn	1.1 fb 1.1 fb 1.1	1	0	848,193	65,009
S-metolachlor fb prometryn fb prometryn	0.7 fb 1.1 fb 1.1	7	0	849,090	52,075
Pendimethalin fb prometryn fb *S*-metolachlor	1.1 fb 1.1 fb 1.1	0	0	987,168	62,222
Ethofumesate fb prometryn fb prometryn	1.5 fb 1.1 fb 1.1	1	0	808,742	51,892
Pendimethalin fb ethofumesate fb prometryn	1.1 fb 2 fb 1.1	13	0	914,542	63,651
Pendimethalin fb *S*-metolachlor fb prometryn	1.1 fb 1.1 fb 1.1	3	0	849,986	58,312

[a]Abbreviations: DAS, d after seeding; fb, followed by.
[b]Three herbicide applications were included in each program: PRE fb POST at 3-carrot leaf growth stage fb POST at 5-carrot leaf growth stage. All prometryn applications included nonionic surfactant applied at 0.5% v/v.

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Table 6. Visible estimation of carrot injury and carrot root yield grown on coarse-textured, low organic matter soil in Hancock, WI, in 2016.[a]

Program[b]	Herbicide rate	Injury[c]		Carrot root	
		59 DAS	71 DAS	Number	Yield
	kg ai ha−1	%		plant ha^{-1}	kg ha^{-1}
Nontreated	–	0	0	225,950	6,680
Hand weeded	–	0	0	609,700	74,370
Pendimethalin fb prometryn fb prometryn	1.1 fb 1.1 fb 1.1	0 b	0 b	619,260	74,440 ab
S-metolachlor fb prometryn fb prometryn	0.7 fb 1.1 fb 1.1	13 a	4 a	462,650	59,900 c
Pendimethalin fb prometryn fb *S*-metolachlor	1.1 fb 1.1 fb 1.1	0 b	0 b	586,980	83,560 a
Ethofumesate fb prometryn fb prometryn	1.5 fb 1.1 fb 1.1	10 a	10 a	490,150	70,910 abc
Pendimethalin fb ethofumesate fb prometryn	1.1 fb 2 fb 1.1	13 a	13 a	502,100	68,430 bc
Pendimethalin fb *S*-metolachlor fb prometryn	1.1 fb 1.1 fb 1.1	0 b	0 b	600,130	84,110 a

[a]Abbreviations: DAS, d after seeding; fb, followed by.
[b]Three herbicide applications were included in each program: PRE fb POST at 3-carrot leaf growth stage fb POST at 5-carrot leaf growth stage. All prometryn applications included nonionic surfactant applied at 0.5% v/v.
[c]Means followed by the same letter are not different according to Fisher's protected LSD test at P = 0.05. If no letters are included for a column, then no statistical differences were noted.

than 2015, as noted earlier, suggesting that herbicide selectivity between carrot and target weeds is marginal. The carrot injury was most persistent where ethofumesate was applied PRE or POST and consisted primarily of stunted plants.

The highest labeled rate of prometryn (2.2 kg ai ha^{-1}) was evaluated on muck soil in 2015, given the general knowledge that herbicides are often much less effective in managing weeds on high organic matter soils, even when applied POST. However, selectivity between carrot and target weeds was poor at this rate, and injury ranged from 20% to 60% at 55 and 69 DAS (unpublished data). In 2016, the prometryn rate on muck soil was adjusted to the same as that evaluated on the coarse-textured soil (1.1 kg ai ha^{-1}), and injury by 82 DAS was minimal and similar to that of hand-weeded carrot with all programs (unpublished data). While these observations are from studies without replicated prometryn rates and should be considered preliminary, it is worth noting that prometryn is quite active on high organic matter soils, and application rates should be tested before widespread use.

Carrot root yield

In 2015, the quantity of harvested carrot roots and overall root yield did not differ among weed management programs (Table 5). Carrot root yield where weeds were not treated was less than 25% of yield where weeds were hand weeded, emphasizing the need for effective weed management programs. In 2016, carrot root yield was lowest where *S*-metolachlor was applied PRE or ethofumesate POST, presumably due to poor early-season common lambsquarters control (Table 6).

Wind erosion and subsequent seedling carrot damage are common risks in many production regions, particularly where the crop is grown on coarse-textured, low organic matter soils. It is common practice in that case to seed a small grain "nurse" crop between carrot rows around the time of carrot seeding, such that the small grain plants slow or catch windblown sand. In related research conducted in 2015 and 2016, we evaluated wheat (*Triticum aestivum* L.), oat, and barley (*Hordeum vulgare* L.) response to PRE applications of the herbicides included in the programs summarized here. Nurse crop injury was minimal where *S*-metolachlor, pendimethalin, or prometryn was applied at rates labeled for PRE use in carrot, with the exception of where prometryn was applied above 1.1 kg ai ha^{-1} (unpublished data).

These studies demonstrate that season-long weed control without compromising yield is possible with weed management programs that include prometryn POST instead of linuron. With that said, a PRE herbicide such as pendimethalin is critical to establish an early-season competitive advantage for carrot plants over weeds, and careful attention should be paid to the prometryn rate, as selectivity is marginal.

In light of potential linuron use rate and pattern changes pending during USEPA registration review and increasing prevalence of resistant weeds, prometryn can be a viable alternative. The current use pattern allows applications up to the 6-leaf carrot growth stage. Beyond that, metribuzin is currently the only broadleaf herbicide option, but some carrot varieties are particularly sensitive, and rotational restrictions can prevent use of metribuzin in some cropping systems. New herbicide active ingredients are few and far between, particularly in specialty crops such as carrot. With this in mind, our current research is focused on competitive carrot cropping systems and natural plant growth regulators that hasten and synchronize carrot emergence, increase canopy development rates, and mitigate injury risk from current herbicides. Such strategies could be integrated with the herbicide programs described here as well as with cultivation used in organic production to diversify management options.

Author ORCID. Jed B. Colquhoun, https://orcid.org/0000-0002-8160-293X

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