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Effect of PRE and POST Herbicides on Carolina Redroot (*Lachnanthes caroliniana*) Growth

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Greenhouse studies were conducted in Raleigh, NC to determine Carolina redroot control by selected PRE and POST herbicides labeled for blueberries. Paraquat, glufosinate, glyphosate, and flumioxazin provided some Carolina redroot shoot control 7 d after POST application (DAPOST) ranging from 48 to 74%. Control 25 DAPOST was greatest for hexazinone at 2.2 kg ai ha^{-1} (90%) followed by glufosinate with 56% control and paraquat and terbacil each with 53% control. Control for most treatments declined between 25 and 63 DAPOST with the exception of glyphosate, which increased to 64%. Carolina redroot shoots per pot were reduced by terbacil, hexazinone at 2.2 kg ha^{-1}, and glyphosate compared with the nontreated check 63 DAPOST. Control of Carolina redroot roots and rhizomes 63 DAPOST ranged from 7 to 68%, with the greatest control provided by terbacil (68%) and hexazinone at 2.2 kg ha^{-1} (64%). Terbacil and hexazinone at 2.2 kg ha^{-1} were the only treatments that reduced both shoot and root/rhizome dry weight compared with the nontreated check.

Nomenclature: Flumioxazin; glufosinate; glyphosate; halosulfuron-methyl; hexazinone; paraquat; *S*-metolachlor; terbacil; Carolina redroot, *Lachnanthes caroliniana* (Lam.) Dandy.
Key words: Blueberry, herbicide rate, residual weed control.

Estudios de invernadero fueron realizados en Raleigh, NC, para determinar el control de *Lachnanthes caroliniana* con varios herbicidas PRE y POST registrados para uso en arándanos (*Vaccinum corymbosum*). Paraquat, glufosinate, glyphosate y flumioxazin brindaron control parcial del tejido aéreo de *L. caroliniana* a 7 días después de la aplicación POST (DAPOST), el cual varió entre 48 y 74%. El mayor control a 25 DAPOST se obtuvo con hexazinone a 2.2 kg ai ha^{-1} (90%) seguido por glufosinate con 56% y paraquat y terbacil cada uno con 53% de control. Para la mayoría de los tratamientos, el control disminuyó entre 25 y 63 DAPOST, con la excepción de glyphosate, el cual aumentó a 64%. El número de tallos de *L. caroliniana* por maceta se redujo con terbacil, hexazinone a 2.2 kg ha^{-1}, y glyphosate al compararse con el testigo no-tratado a 63 DAPOST. El control de raíces y rizomas de *L. caroliniana* a 63 DAPOST varió entre 7 y 68%, obteniéndose el mayor control con terbacil (68%) y hexazinone a 2.2 kg ha^{-1} (64%). Terbacil y hexazinone a 2.2 kg ha^{-1} fueron los únicos tratamientos que redujeron el peso seco de tallos y de raíces/rizomas en comparación con el testigo no-tratado.

North Carolina produced 16.4 million kg of blueberries in 2011 at a farm value of $66 million (NCDA&CS 2012). Blueberry (*Vaccinum corymbosum* L., its hybrids, and *V. ashei* Reade) production in North Carolina is concentrated in the lower Coastal Plain (NCDA&CS 2012) where soil conditions (organic matter > 2%, good drainage, sandy texture, pH 4.0 to 5.0) are optimal for blueberry production. Weeds in blueberry production locations range from annual herbaceous species to herbaceous and woody perennial species (Roberts 2009). Roberts (2009) reported Carolina redroot to be among the most common perennial weed species in 20 commercial blueberry production fields in the lower North Carolina Coastal Plain. A lack of consistent Carolina redroot control is a concern of blueberry growers in the lower Coastal Plain (K. M. Jennings, personal communication). Currently, North Carolina blueberry weed management programs rely heavily upon the use of hexazinone (Roberts 2009), a herbicide that has historically provided inconsistent control of Carolina redroot (K. M. Jennings, unpublished data). The maximum labeled rate of hexazinone for blueberry soils typical of the lower Coastal Plain is 2.8 kg ha^{-1}, with common use rates of 1.1 and 2.2 kg ha^{-1}.

Carolina redroot is a herbaceous, monocotyledonous, perennial, and monotypic genus of the bloodwort family (*Haemodoraceae*) whose common name is derived from the plant's red to orange roots and rhizomes. Leaves of the species are mostly basal, equitant, glabrous, and linear (Radford et al. 1983). Mature plants reportedly reach 0.9 m in height (USDA-NRCS 2013) but typically do not exceed 0.5 m in North Carolina. Inflorescences appear in June through early September as corymbosely arranged branches of compact helicoid cymes (Radford et al. 1983). Carolina redroot is the only member of the bloodwort family native to North America and inhabits wet savannas, pocosin edges, shores of coastal plain depression ponds, and wet disturbed ground (Weakley 2012). Native populations of Carolina redroot have been documented in provinces/states along North America's Atlantic Coast from Nova Scotia south to Florida and in states along the Gulf Coast from Florida west to Louisiana (USDA-NRCS 2013). Although abundant within its native range in North Carolina, the species is listed as endangered in four states (Connecticut, Maryland, New York, and Tennessee),

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Table 1. PRE and POST treatments applied to greenhouse-grown Carolina redroot in Raleigh, NC.

Herbicide	Trade name	Rate ha^{-1}	Manufacturer	Address	Website
Flumioxazin (PRE)	Chateau	430 g ai	Valent U.S.A. Corp.	Walnut Creek, CA	valent.com
Glufosinate (POST)	Rely 280	660 g ai	Bayer CropScience LP	Research Triangle Park, NC	bayercropscience.com
Glyphosate (POST)	Roundup WeatherMax	1.3 kg ae	Monsanto Co.	St. Louis, MO	monsanto.com
Halosulfuron-methyl + NIS[a] (POST)	Sandea	40 g ai	Gowan, Co.	Yuma, AZ	gowanco.com
Hexazinone (PRE)	Velpar	1.1 kg ai 2.2 kg ai	DuPont	Wilmington, DE	cropprotection.dupont.com
Paraquat + NIS (POST)	Gramoxone Inteon	560 g ai	Syngenta Crop Protection, Inc.	Greensboro, NC	syngentacropprotection-us.com
S-Metolachlor (PRE)	Dual Magnum	1.4 kg ai	Syngenta Crop Protection, Inc.	Greensboro, NC	syngentacropprotection-us.com
Terbacil (PRE)	Sinbar	1.8 kg ai	Tessenderlo Kerley, Inc.	Phoenix, AZ	tkinet.com
NIS	X-77	0.25% (v/v)	Loveland Products, Inc	Greeley, CO	lovelandproducts.com

[a] Abbreviation: NIS, nonionic surfactant.

threatened in Rhode Island, and of special concern in Massachusetts (USDA-NRCS 2013).

Information on Carolina redroot control in blueberries is limited. Welker and Brogdon (1968) reported that repeated use of diuron (1.1 and 2.2 kg ai ha^{-1}) and simazine (4.5 kg ai ha^{-1}) in highbush blueberry resulted in satisfactory (89 to 100%) control of a community of weeds, which included Carolina redroot. Meggitt and Aldrich (1959) reported that amitrol at 1.1 kg ai ha^{-1} applied to cranberry bogs in fall immediately after harvest reduced Carolina redroot shoot density 85%. Ferrell et al. (2009) reported that triclopyr (1.1 kg ai ha^{-1}) and a combination of dicamba (560 g ai ha^{-1}) plus 2,4-D (1.6 kg ai ha^{-1}) provided 70 to 85% control of Carolina redroot in pastures. Welker (1979) reported that terbacil provided excellent Carolina redroot control, perfluidone and glyphosate gave good to excellent control, and paraquat gave good initial control, but only fair to good residual control. Monaco (1970) reported that terbacil (PRE at 2.2 to 9 kg ha^{-1}) provided excellent control of Carolina redroot, but rates $\geq$ 4.5 kg ha^{-1} severely injured 'Jersey' blueberry bushes. Meyers et al. (2013) reported that paraquat, glufosinate, and glyphosate POST provided acceptable control of Carolina redroot.

Typically, the distribution of Carolina redroot in commercial blueberry production fields is not uniform and it prevents researchers from obtaining consistent results in on-farm studies. Furthermore, given the nature of field research, observations of the influence of herbicide treatment on Carolina redroot roots and rhizomes may be limited. With that in mind, a greenhouse study was conducted to compare PRE and POST blueberry herbicides on Carolina redroot.

Materials and Methods

Studies were conducted at the Marye Anne Fox Science Teaching Laboratory Greenhouses at North Carolina State University (35.79°N, 78.67°W) in Raleigh, NC in 2012. Carolina redroot plants with an average height of 15 cm were carefully hand-dug from a commercial blueberry field in Burgaw, NC (34.60°N, 77.85°W) on July 11, 2011. Three single shoot divisions containing an average of one 5-cm-long rhizome each were transplanted into 20-cm-diam pots containing 2.4 L of a 1 : 1 (v/v) mix of Fafard 4P potting mix (Conrad Fafard, Inc., Agawam, MA) and nontreated Murville muck (sandy, siliceous, thermic Typic Haplaquods) field soil obtained from the same location as the Carolina redroot plants. The resulting potting mix contained organic matter (11.2%) and pH (4.5) representative of soils found in the lower North Carolina Coastal Plain. After transplanting, Carolina redroot plants were allowed to establish (as determined by foliar growth and a developed root ball that was examined by inverting then dislodging plants from pots not used in the study). Upon successful establishment in late September 2011, the leaves of Carolina redroot plants senesced, indicating the onset of dormancy. The timing of senescence was similar to that observed under field conditions (S. L. Meyers, personal observation). Plants remained dormant under greenhouse and natural day length conditions until spring 2012.

Treatments consisted of five PRE and four POST herbicides, and a nontreated check (Table 1). All herbicides applied were registered for use in blueberry in North Carolina with the exception of *S*-metolachlor. *S*-metolachlor is currently registered for use in blueberry in other blueberry-growing states; its registration for North Carolina blueberry use is anticipated in the near future. The study was conducted twice, with two runs separated temporally. PRE and POST applications were applied to run 1 on February 21 and May 14, 2012, respectively and to run 2 on February 23 and May 4, 2012, respectively. Before PRE herbicide applications, the development of subterranean Carolina redroot shoots were monitored routinely by carefully removing plants not used in the study from their pots. PRE applications were made when Carolina redroot shoots had developed under the soil surface, but before shoots became visible above the soil surface. Treatments were applied in a spray chamber with a CO_2-pressurized sprayer calibrated to deliver 187 L ha^{-1} with a single 8002 EVS nozzle tip (Teejet Technologies, Springfield, IL) at 280 kPa. Following the application of PRE treatments, pots were watered lightly to incorporate soil-applied herbicides but not so much as to allow leaching through the pots. After 2 wk pots were watered as needed to maintain even soil moisture throughout the entire pot. Carolina redroot plants were not watered for 18 h after POST applications to avoid potentially washing herbicide from leaves, after which time pots were watered as needed to maintain even soil moisture.

Table 2. Influence of PRE and POST herbicide applications on Carolina redroot shoot number and control, root/rhizome control, and shoot and root/rhizome dry weight in Raleigh, NC in 2012.

Treatment	Timing	Rate	Shoot control (DAPOST)[a,b]				Shoot number (DAPOST)			
			7	14	25	63	63	Shoot dry weight	Root/rhizome control	Root/rhizome dry weight
		ai or ae ha^{-1}[c]	%				Shoots pot^{-1}	g	%	g
Nontreated check	NA	NA	–	–	–	–	17	3.6	–	4.8
Flumioxazin	PRE	430 g	48	15	5	5	20	4.1	11	3.0
Hexazinone	PRE	1.1 kg	31	24	11	20	14	3.1	35	1.6
Hexazinone	PRE	2.2 kg	9	50	90	40	6	1.3	64	0.7
S-metolachlor	PRE	1.4 kg	3	1	1	1	19	3.9	7	4.8
Terbacil	PRE	1.8 kg	22	40	53	40	9	0.8	68	0.4
Glyphosate	POST	1.3 kg	48	33	38	64	9	2.4	57	2.2
Glufosinate	POST	660 g	62	59	56	30	14	3.1	51	2.0
Halosulfuron-methyl[d]	POST	40 g	7	14	8	6	20	4.3	51	2.2
Paraquat	POST	560 g	74	67	53	24	14	2.4	40	1.3
LSD (0.05)			29	12	19	19	6	0.5	22	0.9

[a] Rating: 0% = no control; 100% = complete control.

[b] Abbreviation: DAPOST, days after POST treatment.

[c] Glyphosate rate is given in weight of ae; all others are weight of ai.

[d] Halosulfuron-methyl and paraquat were applied with 0.25% (v/v) nonionic surfactant.

Pots were maintained weed-free by hand-removing emerged weeds, with the exception of Carolina redroot, weekly. The experimental design was a randomized complete block; both runs contained four replications.

Each pot was treated as a single experimental unit. Data recorded included Carolina redroot shoot number (shoots per pot) 5 and 7 wk after PRE treatments (WAPRE) and 63 d after POST treatments (DAPOST) and visual Carolina redroot control ratings (scale of 0 [no control] to 100% [complete control]) at 7, 14, 25, and 63 DAPOST. Destructive harvest of Carolina redroot plants was conducted 63 DAPOST. Plants were removed from pots, and then soil was hand-removed from plant roots by gentle shaking followed by a steady stream of water applied through a greenhouse breaker nozzle tip. After soil removal, a visual rating for Carolina redroot root/rhizome injury was recorded using the aforementioned scale of 0 to 100%. Shoots were severed from roots and rhizomes at soil level and fresh weight for these structures was separately recorded. Shoots and roots/rhizomes were then placed in paper bags and oven-dried at 107 C for 72 h before determining dry weight.

Data for Carolina redroot shoot number, shoot and root/rhizome control, and shoot and root/rhizome dry weight were subjected to ANOVA and analyzed by SAS PROC GLM (SAS 9.2, SAS Institute, Cary, NC) with the fixed effect of treatment and random effects of run and replication within run. Data for percent Carolina redroot shoot and root/rhizome control were subjected to arcsine transformation; redroot shoot and root/rhizome dry weight data were subjected to square-root transformation. To facilitate the interpretation of results, back-transformed values for Carolina redroot control and dry weight data are presented. When ANOVA indicated a significant treatment effect, means were separated using LSD ($P \leq 0.05$). The nontreated check was included in analysis of Carolina redroot shoot number and shoot and root/rhizome dry weight but was omitted for percent control of visual data. Carolina redroot shoot number data from POST treatments were excluded from shoot counts 5 and 7 WAPRE as POST treatments had not been applied when these observations were recorded.

Results and Discussion

Carolina Redroot Shoot Number and Control. No data had a significant treatment-by-run interaction. Thus, data were analyzed across both runs. Carolina redroot shoot number was not influenced by PRE treatments 5 and 7 WAPRE and ranged from one to four and one to seven shoots per pot 5 and 7 WAPRE, respectively (data not shown). PRE applications of terbacil or hexazinone at 2.2 kg ha^{-1} and glyphosate POST reduced shoot number 63 DAPOST compared with the nontreated check (Table 2). Paraquat, glufosinate, glyphosate, and flumioxazin provided some level of control ranging from 48 to 74% 7 DAPOST. Control from all other treatments 7 DAPOST was $\leq$ 31%. The greatest Carolina redroot control 14 DAPOST was provided by paraquat, glufosinate, and hexazinone at 2.2 kg ha^{-1}. Control 25 DAPOST was greatest for hexazinone at 2.2 kg ha^{-1} (90%), followed by glufosinate, paraquat, and terbacil. Control for most treatments declined between 25 and 63 DAPOST with the exception of glyphosate, which increased from 38 to 64%. It is noteworthy that hexazinone at 2.2 kg ha^{-1} provided greater Carolina redroot control 14, 25, and 63 DAPOST than 1.1 kg ha^{-1}. Many growers currently use 1.1 kg ha^{-1} of hexazinone because they believe it reduces the risk of crop injury that may occur when hexazinone is applied at 2.2 kg ha^{-1}.

Also of note is the delayed response of Carolina redroot to both terbacil and hexazinone at 2.2 kg ha^{-1}. Both treatments displayed increases in visual shoot control between 7 and 14 DAPOST and 14 and 25 DAPOST. Comparisons of this response with other weed species are limited due to the fact that few researchers report weed control results with terbacil

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and hexazinone at such close intervals. However, Teuton et al. (2004) did report a similar response by tropical signalgrass [*Urochloa subquadripara* (Trin.) R. Webster] to hexazinone, but did not speculate as to what was responsible for the delayed control. The authors reported that hexazinone at 0.28 kg ha^{-1} applied PRE provided 45 and 36% tropical signalgrass control 5 WAPRE at two different locations, and control increased to 76 and 56% 8 WAPRE at each location, respectively (Teuton et al. 2004). The delayed control observed in the present study is likely the result of greater longevity of these herbicides.

Root and Rhizome Control. Carolina redroot root/rhizome control 63 DAPOST ranged from 7 to 68% (Table 2). Terbacil (68%), hexazinone at 2.2 kg ha^{-1} (64%), glyphosate (57%), glufosinate (51%), and halosulfuron-methyl (51%) all provided a similar level of control of roots/rhizomes. These data differ slightly from those of Meyers et al. (2013), who reported that glyphosate, glufosinate, and hexazinone POST provided 88, 73, and 62% control of Carolina redroot roots/rhizomes, respectively. As with visual Carolina redroot shoot control, hexazinone at 2.2 kg ha^{-1} provided greater root/rhizome control (64%) than 1.1 kg ha^{-1} (35%).

Shoot and Root/Rhizome Dry Weight. Carolina redroot shoot and root/rhizome dry weights of the nontreated check were 3.6 and 4.8 g, respectively (Table 2). Shoot dry weight was reduced by most treatments applied in the study with the exception of halosulfuron-methyl, flumioxazin, and *S*-metolachlor. Root/rhizome dry weight was reduced by all treatments with the exception of *S*-metolachlor. Terbacil and hexazinone at 2.2 kg ha^{-1} provided the greatest reduction of Carolina redroot shoot (0.8 and 1.3 g, respectively) and root/rhizome (0.4 and 0.7 g, respectively) dry weights. Glyphosate and paraquat moderately reduced shoot dry weight (2.4 g) and glufosinate and 1.1 kg ha^{-1} hexazinone only slightly reduced shoot dry weight (3.1 g). Although hexazinone at 2.2 kg ha^{-1} controlled Carolina redroot shoots more effectively than 1.1 kg ha^{-1}, root/rhizome dry weights of both treatments were statistically similar. Hexazinone at 1.1 kg ha^{-1} displayed a disproportionate reduction of roots/rhizomes relative to the shoot dry weight reduction it provided. Similar results were observed by Meyers et al. (2013), who reported that hexazinone at 1.1 kg ha^{-1} applied POST reduced Carolina redroot root/rhizome dry weight, but not shoot dry weight.

In the present study, visual weed control was poor. Hexazinone at 2.2 kg ha^{-1} provided the greatest Carolina redroot control at any given observation (90% 25 DAPOST) (Table 2). Paraquat and glufosinate provided moderate control ($\geq$ 53%) 7 to 25 DAPOST, but control was transient and by 63 DAPOST was reduced to $\leq$ 30%. Terbacil and hexazinone at 2.2 kg ha^{-1} provided the greatest control of roots/rhizomes and resulted in the greatest reduction of both shoot and root/rhizome dry weights; paraquat provided statistically similar reductions in root/rhizome dry weight. Throughout the duration of the study hexazinone at 2.2 kg ha^{-1} outperformed hexazinone at 1.1 kg ha^{-1}. Blueberry growers in North Carolina are currently applying reduced rates of hexazinone due to concern of reduction in blueberry bush vigor when full rates of hexazinone are used. Data from the present study suggest that a lower rate of hexazinone may not provide acceptable redroot control when used alone. For those growers who experience a reduction in blueberry bush vigor due to a higher rate of hexazinone, it must be determined if the decrease in bush vigor is compensated by the increase in Carolina redroot control. This determination is complicated by a lack of data documenting the impact of Carolina redroot interference on blueberry yield and quality. When applied PRE alone, *S*-metolachlor appears to provide no control of Carolina redroot. This result is similar to what Monaco (1970) reported for alachlor PRE at 2.2 kg ha^{-1}, which provided 0% control of Carolina redroot.

Greatly reduced roots/rhizomes should limit the Carolina redroot's ability to regenerate by vegetative means. Vegetative reproduction (plantlets arising from underground rhizomes) appears to be the primary means by which Carolina redroot populations proliferate in blueberry production systems. Meggitt and Aldrich (1959) reached a similar conclusion stating that, "Control of redroot with amitrol was effective in the second and third year following treatment which indicates control is primarily a problem of eliminating existing plants and not a problem of controlling seedlings which arise from seed." As single applications of individual herbicides applied in the present study provided limited control, further studies should determine the influence of sequential control measures (mechanical, chemical, and cultural) and synergistic tank mixtures on longer-term Carolina redroot control.

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