J. Aquat. Plant Manage. 46: 154-158

Response of Selected Aquatic Invasive Weeds to Flumioxazin and Carfentrazone-ethyl

ROBERT J. RICHARDSON, R. L. ROTEN, A. M. WEST, S. L. TRUE AND A. P. GARDNER[1]

ABSTRACT

Two greenhouse trials were conducted to determine the response of selected aquatic weed species to foliar applications of flumioxazin {2-[7-fluoro-3,4-dihydro-3-oxo-4-(2-propynyl)-2H-1,4-benzoxazin-6-yl]-4,5,6,7-tetrahydro-1H-isoindole-1,3(2H)-dione} and carfentrazone-ethyl (a,2-dichloro-5-[4-(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1*H*-1,2,4-triazol-1-yl]-4-fluorobenzenepropanoic acid, ethyl ester). In trial one, flumioxazin and carfentrazone-ethyl were evaluated on the emergent species alligatorweed (*Alternanthera philoxeroides* [Martius] Grisebach), creeping water primrose (*Ludwigia grandiflora* [M. Micheli] Greuter & Burdet ssp. *hexapetala* [Hook. & Arn.] Nesom & Kartesz), and parrotfeather (*Myriophyllum aquaticum* [Vell.] Verdc.). In trial two, flumioxazin was evaluated on the floating species giant salvinia (*Salvinia molesta* D.S. Mitchell) and water lettuce (*Pistia stratiotes* L.). In both trials flumioxazin was applied at 0, 34, 168, 302, and 437 g ai/ha, while carfentrazone-ethyl was applied only in the first trial at 0, 56, 112, and 224 g ai/ha. At 4 weeks after treatment (WAT), flumioxazin controlled alligatorweed, giant salvinia, and water lettuce at least 91% with rates of 168 g ai/ha or higher. Creeping water primrose and parrotfeather were controlled 73 to 81% with 437 g ai/ha. Calculated EC_{90} flumioxazin values were 35.6 g ai/ha for alligatorweed and 70.3 g ai/ha for water lettuce. Creeping water primrose, giant salvinia, and parrotfeather EC70 values were 120, 256, and 164 g ai/ha, respectively. Carfentrazone-ethyl did not control

[1]Assistant Professor, Research Associate, Graduate Research Assistant, Graduate Research Assistant, and Research Assistant, North Carolina State Univ., Box 7620, Raleigh, NC 27695; e-mail: rob_richardson@ncsu.edu.
Received for publication January 20, 2008 and in revised form May 9, 2008.

alligatorweed, creeping water primrose, or parrotfeather greater than 64% at the rates evaluated.

Key words: alligatorweed, creeping water primrose, giant salvinia, parrotfeather, water lettuce, dose response, herbicide efficacy, protoporphyrinogen oxidase (PPO) inhibitor.

INTRODUCTION

Numerous invasive aquatic weeds are present in North Carolina and the Mid-Atlantic region of the United States. These include alligatorweed (*Alternanthera philoxeroides* [Martius] Grisebach), creeping water primrose (*Ludwigia grandiflora* [M. Micheli] Greuter & Burdet ssp. *hexapetala* [Hook. & Arn.] Nesom & Kartesz), giant salvinia (*Salvinia molesta* D.S. Mitchell), parrotfeather (*Myriophyllum aquaticum* [Vell.] Verdc.), and water lettuce (*Pistia stratiotes* L.; Richardson et al. 2007; USDA 2008). Each of these species can form dense infestations, displacing native plants and animals and disrupting normal water body functions. Management of these species in North Carolina is primarily by herbicides because the few available host-specific biocontrol agents have generally not provided acceptable control (R. Richardson, pers. observ.).

Currently, only 11 active ingredients are registered for aquatic plant management. These products do not control all aquatic weed species under all field conditions, and additional herbicides with unique modes of action are needed. Flumioxazin is an *N*-phenylphthalimide herbicide currently being evaluated for aquatic plant management (Mossler and Langeland 2006). This herbicide inhibits protoporphyrinogen oxidase (PPO, EC 1.3.3.4; Yoshida et al. 1991), similar to the currently registered aquatic herbicide carfentrazone-ethyl (Koschnick et al. 2004). The PPO inhibitors are reported to cause porphyrin accumulation in susceptible plants resulting in photosensitization and membrane lipid peroxidation (Vencill 2002). Whole plant symptoms are characterized by quick dessication and necrosis of treated foliage (Vencill 2002). Flumioxazin has been evaluated for use in many crops, including cotton (*Gossypium hirsutum* L.), peanut (*Arachis hypogaea* L.), potato (*Solanum tuberosum* L.), soybean (*Glycine max* [L.] Merr.), sugarcane (*Saccharum* spp.), orchards, vineyards, certain ornamentals, and noncropland (Cranmer et al. 2000, Askew et al. 2002, Burke et al. 2002, Taylor-Lovell et al. 2002, Wilson et al. 2002, Dunst et al. 2004, Zandstra and Particka 2004, Anonymous 2005, Richardson and Zandstra 2006).

Due to the need for increased management options for alligatorweed, creeping water primrose, giant salvinia, parrotfeather, and water lettuce, we evaluated the response of each species to flumioxazin as a foliar application and the response of alligatorweed, creeping water primrose, and parrotfeather to carfentrazone-ethyl.

MATERIALS AND METHODS

In study one, alligatorweed, creeping water primrose, and parrotfeather shoot tips (approximately 5 to 10 cm in length) were transplanted into 9-cm square pots containing a commercial potting mix (Metro Mix® 200; Sun Gro Horticulture, Bellevue, WA). Pots were maintained saturated by frequent irrigation and fertilized weekly with Miracle-Gro® Water Soluble Lawn Food (36-6-6; The Scotts Company, Marysville, OH). Plants were allowed to establish root systems and begin shoot growth prior to treatment at approximately 15 to 20 cm of height. Treatments included carfentrazone-ethyl (Stingray®; FMC Corporation, Philadelphia, PA) at 0, 56, 112, and 224 g ai/ha, and flumioxazin (flumioxazin 51WDG; Valent USA Corporation, Walnut Creek, CA) at 0, 34, 168, 302, and 437 g ai/ha. Treatments were applied with a single Teejet® XR8003 flat-fan nozzle (Spraying Systems Company, Wheaton, IL) at 280 L/ha spray volume and pressurized with CO_2. Herbicide solutions were mixed immediately prior to application, and each included nonionic surfactant (Induce®; Helena Chemical Co., Collierville, TN) at 0.5% v/v.

In study two, giant salvinia and water lettuce were cultured in greenhouse mesocosms at North Carolina State University. Plants of uniform size were placed in 3.74-L buckets containing pond water and allowed to acclimate for three days. Giant salvinia coverage was approximately 90% and water lettuce diameter was approximately 9 cm at time of treatment. Plants were transferred to 91 by 60 cm flats containing tap water for treatment. Flumioxazin rates included 0, 34, 168, 302, and 437 g ai/ha. Treatments included nonionic surfactant and were applied with methods equivalent to study one. After treatment, plant foliage was allowed to dry for approximately 1 hour prior to placement back in buckets. Fertilization was not needed because control plants maintained active growth throughout the course of the trial.

Each study was repeated in time and included four treatment replications. In each study, visual estimates of weed control were determined at 1 and 4 weeks after treatment (WAT) on a 0 to 100% scale, where 0% equals no plant response and 100% equals complete plant death. At 4 WAT, plant shoots (alligatorweed, creeping water primrose, and parrotfeather) or whole plants (giant salvinia and water lettuce) were harvested and air-dried to constant moisture prior to dry weight determination. Percent weed control data were arcsine square root transformed prior to analysis, but non-transformed means are presented for clarity.

Data were subjected to analysis of variance, and means were separated using Fisher's Protected LSD ($P \le 0.05$) in SAS v. 9.1 (SAS Institute, Inc., Cary, NC). The non-treated control was not included in statistical analyses of visual ratings, but was included in dry weight analyses. All data were combined as a treatment by trial repetition interaction was not observed. Plant dry weight data were subjected to regression analysis using the logistic equation $y = a/1 + (x/x_o)^b$ in SigmaPlot 9.01 (Systat Software, Inc., Point Richmond, CA). Regression models were then used to calculate effective concentrations reducing dry weight to 70 or 90% of non-treated control dry weights values (EC_{70} and EC_{90}, respectively). Values for EC_{70} were calculated because regression curves did not cross 90% dry weight reduction points for creeping water primrose, parrotfeather, or giant salvinia. Linear and quadratic contrasts were used in SAS v. 9.1 to evaluate the significance of carfentrazone-ethyl rate.

RESULTS AND DISCUSSION

At 1 WAT, carfentrazone-ethyl controlled alligatorweed 72, 84, and 92% with 56, 112 g ai/ha, and 224 g/ha, respectively, but control was only 40 to 64% at 4 WAT (Table 1). Flumiox-

TABLE 1. CONTROL AND DRY WEIGHTS OF ALLIGATORWEED, CREEPING WATER PRIMROSE, AND PARROTFEATHER AFTER FOLIAR APPLICATIONS OF FLUMIOXAZIN.[a,b]

Herbicide[c]	Rate	Alligatorweed			Creeping water primrose			Parrotfeather		
		1 WAT[d]	4 WAT	Dry wt.	1 WAT	4 WAT	Dry wt.	1 WAT	4 WAT	Dry wt.
	g ai/ha	---------- % ----------		g	---------- % ----------		g	---------- % ----------		g
Carfentrazone-ethyl	56	72 c	40 d	0.46 b	51 c	26 c	1.08 b	48 b	26 b	0.82 bc
Carfentrazone-ethyl	112	84 bc	58 c	0.26 bc	56 bc	42 b	0.95 bc	48 b	18 b	0.88 b
Carfentrazone-ethyl	224	92 ab	64 bc	0.21 cd	62 ab	41 b	0.83 bcd	63 ab	35 b	0.55 cd
Flumioxazin	34	94 ab	78 b	0.13 cd	49 c	32 bc	0.95 bc	43 b	28 b	0.74 bc
Flumioxazin	168	98 a	98 a	0.00 d	64 ab	70 a	0.54 cde	75 a	71 a	0.31 d
Flumioxazin	302	98 a	100 a	0.00 d	63 ab	76 a	0.41 de	74 a	74 a	0.33 d
Flumioxazin	437	98 a	99 a	0.01 d	69 a	81 a	0.39 e	77 a	73 a	0.29 d
Non-treated	—	0	0	1.08 a	0	0	1.84 a	0	0	1.43 a
Carfentrazone-ethyl rate significance										
Linear		NS	0.0322	0.0346	0.0102	NS	NS	NS	NS	NS
Quadratic		NS	NS	NS	NS	NS	NS	NS	NS	NS

[a]Weed control rated on 0 to 100% scale; 0% = no plant response and 100% = complete death.
[b]Abbreviations: WAT, weeks after treatment.
[c]Non-ionic surfactant at 0.5% v/v included with all herbicide applications.
[d]Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD (P ≤ 0.05). Mean separation should be used for comparison of carfentrazone-ethyl to flumioxazin.

azin controlled alligatorweed 94 to 98% at 1 WAT. At 4 WAT, 34 g ai/ha flumioxazin controlled alligatorweed 78%, and control increased to 98% or greater with rates of 168 to 437 g ai/ha. Non-treated alligatorweed dry weight was 1.08 g and decreased in a linear fashion to 0.46, 0.26, and 0.21 g with 56, 112, and 224 g ai/ha carfentrazone-ethyl, respectively. Alligatorweed dry weight was 0 to 0.01 g with 168 to 437 g ai/ha flumioxazin (Figure 1). Calculated EC_{70} and EC_{90} values for alligatorweed were 22.8 and 35.6 g ai/ha flumioxazin, respectively (Table 2). Amaranthaceae species have also been sensitive to flumioxazin in terrestrial settings. Common waterhemp (*A. rudis* Sauer), Palmer amaranth (*A. palmeri* S. Wats.), redroot pigweed (*A. retroflexus* L.), smooth pigweed (*A. hybridus* L.), spiny amaranth (*A. spinosus* L.), and tall waterhemp (*A. tuberculatus* [Moq.] Sauer) have been controlled with preemergence and/or postemergence flumioxazin applications at rates ranging from 35 to 110 g ai/ha (Niekamp and Johnson 2001, Askew et al. 2002, Price et al. 2002, Wilson et al. 2002, Shoup and Al-Khatib 2004, Grichar 2006, Kelly et al. 2006). However, these are all annual species, and further research should be conducted to determine field efficacy of flumioxazin on the perennial Amaranthaceae alligatorweed.

TABLE 2. FLUMIOXAZIN 70 AND 90% EFFECTIVE CONCENTRATIONS CALCULATED FROM NON-LINEAR REGRESSION CURVES.

	EC_{70}	EC_{90}
Alligatorweed	22.8	35.6
Creeping water primrose	120.0	—[a]
Giant salvinia	256.0	—[a]
Parrotfeather	164.0	—[a]
Water lettuce	23.9	70.3

[a]Regression curve did not extend to 90% control level.

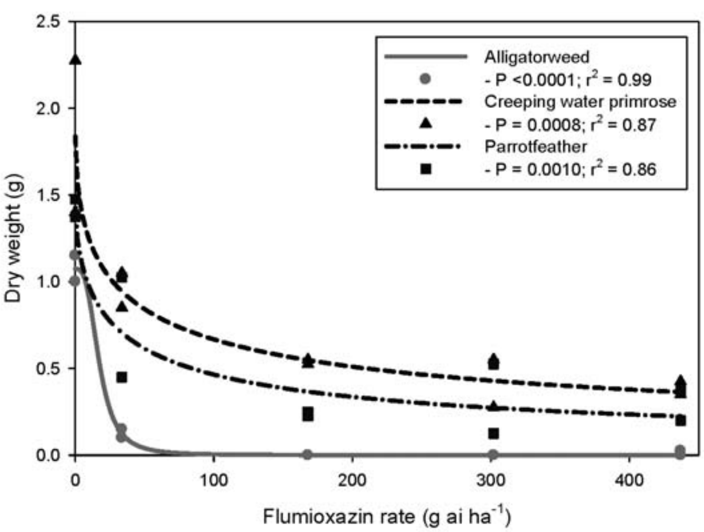

Figure 1. Greenhouse response of alligatorweed, creeping water primrose, and parrotfeather dry weights to increasing foliar-applied flumioxazin rate at 4 weeks after treatment. Curves generated using the logistic equation $y = a/1 + (x/x_o)^b$.

Creeping water primrose control at 4 WAT and dry weight were not influenced by carfentrazone-ethyl rate (Table 1). Dry weight was reduced to 59% of the non-treated with 56 g ai/ha carfentrazone-ethyl. Control with flumioxazin was 49 to 69% at 1 WAT. At 4 WAT, 168 to 437 g ai/ha flumioxazin controlled creeping water primrose 70 to 81%. Creeping water primrose dry weight was 1.84 g when non-treated and decreased to 0.39 g with 437 g ai/ha (Figure 1). Extrapolated EC_{70} for creeping water primrose was 120 g ai/ha flumioxazin (Table 2).

Carfentrazone-ethyl rate did not affect parrotfeather control (Table 1). Parrotfeather dry weight was reduced to 38% of the control when treated with 224 g ai/ha carfentrazone-ethyl. Flumioxazin rates of 168 to 437 g ai/ha controlled parrotfeather 71 to 77% at 1 and 4 WAT. Parrotfeather dry weight was 22% of control dry weight when treated with 168 g ai/ha flumioxazin, and increased rate provided little to no benefit (Figure 1). Calculated EC_{70} for parrotfeather was 164 g ai/ha flumioxazin (Table 2). In previous mesocosm trials, parrotfeather was initially controlled with carfentrazone-ethyl in-water applications of 100 ppm or greater, and biomass was reduced from the non-treated (Gray et al. 2007). In addition, variable-leaf milfoil (*Myriophyllum heterophyllum* Michx.) biomass was significantly reduced with in-water applications of 100 to 200 ppm carfentrazone-ethyl (Glomski and Netherland 2007), while Eurasian watermilfoil (*M. spicatum* L.) was controlled at least 98% with 150 or 200 ppm (Gray et al. 2007). Carfentrazone-ethyl has also been observed to have efficacy on variable-leaf milfoil (*Myriophyllum heterophyllum* Michaux) under North Carolina field conditions (Richardson, unpubl. data).

At 1 WAT, flumioxazin controlled giant salvinia 50 to 56% (data not presented). Control at 4 WAT was 91 to 97% with 168 to 437g ai/ha flumioxazin, but only 63% with 34 g ai/ha. Giant salvinia dry weight was 2.04 g when non-treated, and declined to 0.49 g with 437 g ai/ha flumioxazin (Figure 2). The EC_{70} for giant salvinia was calculated to be 256 g ai/ha flumioxazin (Table 2). Disparity between visual ratings and dry weight reduction may be attributed to remaining dead biomass from initial salvinia dry weight present at time of flumioxazin application rather than lack of efficacy. In previous research, carfentrazone-ethyl at 112 to 224 g ai/ha controlled giant salvinia 97% or greater at 4 WAT (Glomski and Getsinger 2006), and Koschnick et al. (2004) reported an EC_{90} of 79.1 g ai/ha for carfentrazone-ethyl on *Salvinia minima* Baker.

Water lettuce control at 1 WAT was 87% with 34 g ai/ha flumioxazin and increased to 98% with 437 g/ha flumioxazin (data not presented). At 4 WAT, control was 97% with 34 g ai/ha flumioxazin and 100% with higher rates. Water lettuce dry weight was 1.36 g when non-treated, 0.3 g when treated with 34 g ai/ha flumioxazin, and 0.08 g or less with higher rates (Figure 2). Extrapolated EC_{90} for water lettuce was 70.3 g ai/ha flumioxazin (Table 2). In previous research, water lettuce had a calculated EC_{90} value of 26.9 and 33 g ai/ha carfentrazone-ethyl across two trials (Koschnick et al. 2004).

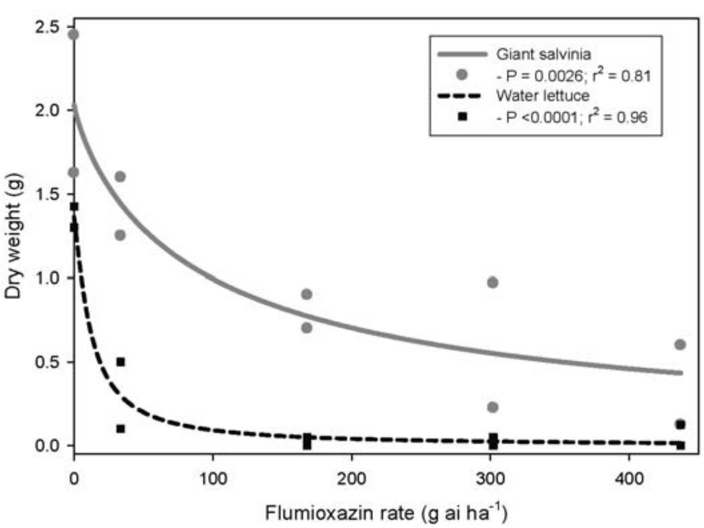

Figure 2. Greenhouse response of giant salvinia and water lettuce dry weights to increasing foliar-applied flumioxazin rate at 4 weeks after treatment. Curves generated using the logistic equation $y = a/1 + (x/x_o)^b$.

In conclusion, flumioxazin controlled alligatorweed, giant salvinia, and water lettuce in the greenhouse and suppressed creeping water primrose and parrotfeather at rates of 34 to 437 g/ha. However, increased flumioxazin rate above 168 g/ha generally was of little benefit. Carfentrazone-ethyl did not control alligatorweed, creeping water primrose, or parrotfeather at the rates evaluated, but did reduce alligatorweed biomass to 19% of the non-treated. Although alligatorweed regrew rapidly following carfentrazone-ethyl application, higher rates could potentially provide adequate control as alligatorweed also regrew from 34 g ai/ha flumioxazin, but not higher rates. While greenhouse results indicate strong potential for commercial use of flumioxazin on these five weed species, additional research should be conducted in the field to further quantify species response to flumioxazin. Field efficacy may differ from greenhouse results due to environmental conditions, spray interception by non-target foliage, and other factors. In-water applications of flumioxazin should also be evaluated and published for efficacy on these and other aquatic weed species.

ACKNOWLEDGMENTS

The authors would like to thank Jenny Johnson for technical assistance with portions of this research. We also thank Valent U.S.A. Corporation for partial funding of this project.

LITERATURE CITED

Askew, S. D., J. W. Wilcut and J. R. Cranmer. 2002. Cotton (*Gossypium hirsutum*) and weed response to flumioxazin applied preplant and postemergence directed. Weed Technol. 16:184-190.

Burke, I. C., S. D. Askew and J. W. Wilcut. 2002. Flumioxazin systems for weed management in North Carolina peanut (*Arachis hypogaea*). Weed Technol. 16:184-190.

Cranmer, J. R., J. V. Altom, J. C. Braun and J. A. Pawlak. 2000. Valor herbicide: a new herbicide for weed control in cotton, peanuts, soybeans, and sugarcane. Proc. South. Weed Sci. Soc. 53:158.

Dunst, R. M., T. R. Bates and G. W. Kirfman. 2004. Effectiveness of flumioxazin for weed control in vineyards. Proc. Northeast Weed Sci. Soc. 58:142.

Glomski, L. A. M. and K. D. Getsinger. 2006. Carfentrazone-ethyl for control of giant salvinia. J. Aquat. Plant Manage. 44:136-138.

Glomski, L. M. and M. D. Netherland. 2007. Efficacy of diquat and carfentrazone-ethyl on variable-leaf milfoil. J. Aquatic. Plant Manage. 45:136-138.

Gray, C. J., J. D. Madsen, R. M. Wersal and K. D. Getsinger. 2007. Eurasian watermilfoil and parrotfeather control using carfentrazone-ethyl. J. Aquatic. Plant Manage. 45:43-46.

Grichar, W. J. 2006. Weed control and grain sorghum tolerance to flumioxazin. Crop Protection 25:174-177.

Kelly, S. T., M. W. Shankle and D. K. Miller. 2006. Efficacy and tolerance of flumioxazin on sweetpotato (*Ipomea batatas*). Weed Technol. 20:334-339.

Koschnick, T. J., W. T. Haller and A. W. Chen. 2004. Carfentrazone-ethyl pond dissipation and efficacy on floating plants. J. Aquatic. Plant Manage. 42:103-108.

Mossler, M. A. and K. A. Langeland. 2006. Florida crop/pest management profile: aquatic weeds. University of Florida IFAS Extension. http://edis.ifas.ufl.edu/pdffiles/PI/PI17500.pdf. Accessed Jan. 8, 2008.

Niekamp, J. W. and W. G. Johnson. 2001. Weed management with sulfentrazone and flumioxazin in no-tillage soyabean (*Glycine max*). Crop Protection 20:215-220.

Price, A. J., J. W. Wilcut and J. R. Cranmer. 2002. Flumioxazin preplant burndown weed management in strip-tillage cotton (*Gossypium hirsutum*) planted into wheat (*Triticum aestivum*). Weed Technol. 16:762-767.

Richardson, R. J. and B. H. Zandstra. 2006. Evaluation of flumioxazin and other herbicides for weed control in gladiolus. Weed Technol. 20:394-398.

Richardson, R. J., A. P. Gardner, S. T. Hoyle and A. M. West. 2007. Invasive aquatic weeds in North Carolina. Proc. Northeast. Weed Sci. Soc. 61:18.

Shoup, D. E. and K. Al-Khatib. 2004. Control of protoporphyrinogen oxidase inhibitor-resistant common waterhemp (*Amaranthus rudis*) in corn and soybean. Weed Technol 18:332-340.

Taylor-Lovell, S., L. M. Wax and G. Bollero. 2002. Preemergence flumioxazin and pendimethalin and postemergence herbicide systems for soybean (*Glycine max*). Weed Technol. 16:502-511.

Valent Corporation. 2005. Chateau herbicide label. Valent U.S.A. Corporation, Walnut Creek, CA. 15 pp.

Wilson, D. E., S. J. Nissen and A. Thompson. 2002. Potato (*Solanum tuberosum*) variety and weed response to sulfentrazone and flumioxazin. Weed Technol. 16:567-574.

USDA, NRCS (U.S. Department of Agriculture, Natural Resources Conservation Service). 2008. The PLANTS Database (http://plants.usda.gov, 8 January 2008). National Plant Data Center, Baton Rouge, LA 70874-4490 USA.

Vencill, W. K. 2002. Herbicide Handbook. 8th ed. Weed Science Society of America, Lawrence, KS. 493 pp.

Yoshida, R., M. Sakaki, R. Sato, T. Haga, E. Nagano, H. Oshio and K. Kamoshita. 1991. S-53482: a new N-phenyl phthalimide herbicide. Proc. Brighton Crop Prot. Conf. Weeds 1:69-75.

Zandstra, B. H. and M. G. Particka. 2004. New herbicides for weed control in fruit trees. Proc. North Central Weed Sci. Soc. 59:161.