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Notes

Evaluations of foliar applied herbicides for alligatorweed (*Alternanthera philoxeroides*) control

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INTRODUCTION

Alligatorweed [*Alternanthera philoxeroides* (Mart.) Griseb.] is an invasive aquatic plant native to South America (Vogt et al. 1979) that has become a nuisance in the southern United States (Kay and Haller 1982). Alligatorweed exhibits two distinct morphological growth forms, an aquatic form or a terrestrial form (Kay and Haller 1982). The aquatic form produces long leaves and large, hollow stems that provide buoyancy in aquatic settings where plants form an impenetrable mat (Spencer and Coulson 1976, Wain et al. 1984). The terrestrial form has shorter leaves and more lignified stems that are smaller in diameter and lack aerenchyma (Julien and Bourne 1988, Julien and Chan 1992). Alligatorweed reproduces primarily by vegetative means in the United States, although reproduction by seed has been documented in South America (Julien et al. 1995, Holm et al. 1997).

When stems become fragmented, floating sections of alligatorweed may drift to new locations and root in available substrate (Sainty et al. 1998). The presence of alligatorweed increases flood risk, reduces water quality, clogs irrigation canals, and increases water loss caused by evapotranspiration, resulting in increased production costs for agricultural systems (Gangstad et al. 1975, Carpenter 1980, James et al. 2001). Ecosystem services provided by wetland habits are negatively impacted by alligatorweed through reductions in light penetration, a decrease in dissolved oxygen, competition for nutrients, and reductions in habitat complexity (Quimby and Kay 1977, Vogt et al. 1992, Buckingham 1996, Holm et al. 1997).

Various management techniques have been used to control alligatorweed. Mechanical harvesting and physical removal via hand-pulling have proven to be unsuccessful for controlling alligatorweed because of fragmentation of the plant, which further exacerbates spreading (Holm et al. 1997). The alligatorweed flea beetle (*Agasicles hygrophila* Selman and Vogt) has been successful against alligatorweed in temperate climates but not in northern locations where mean winter temperatures fall below 11.1 C (Coulson 1977, Vogt et al. 1992). Herbicides have also been widely used for management of this invasive species.

Penoxsulam, applied at 0.035 kg ha^{-1}, provided biomass reductions of alligatorweed greater than 70% 42 d after treatment (DAT); though control decreased as temperatures increased (Willingham et al. 2008). Applications of 2,4-D (Eggler 1953) and glyphosate (Kay 1999) have been evaluated for control of alligatorweed. Glyphosate is the most common herbicide used for alligatorweed control, though poor translocation to roots and rhizomes, dilution, metabolism, and exudation by roots has been reported in alligatorweed and may limit glyphosate efficacy (Bowmer et al. 1993, Tucker et al. 1994). Imazapyr applied at 1.04 kg ae ha^{-1} provided better control of alligatorweed than triclopyr amine at 5.18 kg ae ha^{-1} when applied in early spring (Allen et al. 2007). West et al. (2008) reported excellent control ($> 85\%$) of alligatorweed 9 WAT with applications of imazapyr alone (0.5% v/v), triclopyr alone (1.5, 3, and 4.5% v/v), and a combination of imazapyr + triclopyr (1.5% v/v).

Because of the unreliable control of alligatorweed with some herbicides and poor translocation with glyphosate, research is needed to identify additional options for effective control. Relying on a single class of herbicide alone may result in herbicide resistance in the future; therefore, alternate chemical options need to be identified to maintain herbicide stewardship. Therefore, objective of this study was to screen available aquatic labeled herbicides that can be applied to the foliage of alligatorweed.

MATERIALS AND METHODS

The study was conducted in 76, 240-L mesocosms (i.e., experimental water enclosures or tanks that provide a limited body of water with manipulated environmental conditions) at the R. R. Foil Plant Science Research Facility, Mississippi State University, for a 12-wk period from June to

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Table 1. Mean dry weight biomass (g) per pot of alligatorweed following foliar aquatic herbicide applications.

Herbicide treatment	Mean Dry Weight (g/pot) Weeks After Treatment (WAT)[1,2] 4	8	12	Biomass reduction 12 WAT (% of Reference)
Carfentrazone-ethyl 0.11 kg ai ha^{-1}	11.1 bc	19.2 b	34.8 c	56
Carfentrazone-ethyl 0.22 kg ai ha^{-1}	14.0 b	17.7 b	51.3 b	35
Diquat 2.24 kg ai ha^{-1}	6.7 cde	12.0 c	45.1 bc	42
Diquat 4.48 kg ai ha^{-1}	4.4 de	3.6 de	4.7 de	94
Glyphosate (IPA salt) 2.27 kg ae ha^{-1}	3.4 e	3.6 de	7.5 de	90
Glyphosate (IPA salt) 4.54 kg ae ha^{-1}	2.4 e	2.8 de	4.2 e	95
Imazamox 0.28 kg ae ha^{-1}	2.0 e	0.3 e	2.0 e	98
Imazamox 0.56 kg ae ha^{-1}	2.7 e	1.3 de	3.1 e	96
Imazapyr 0.56 kg ae ha^{-1}	1.3 e	1.8 e	0.0 e	99
Imazapyr 1.12 kg ae ha^{-1}	1.3 e	0.1 e	0.3 e	99
Penoxsulam 0.05 kg ai ha^{-1}	9.8 bcd	10.1 c	17.5 d	78
Penoxsulam 0.10 kg ai ha^{-1}	10.5 bc	6.9 cd	9.8 de	87
Triclopyr 3.36 kg ae ha^{-1}	2.0 e	3.3 de	4.2 e	95
Triclopyr 6.72 kg ae ha^{-1}	4.0 de	0.8 e	3.8 e	95
2,4-D 1.06 kg ae ha^{-1}	3.7 e	1.0 de	7.0 de	91
2,4-D 2.13 kg ae ha^{-1}	2.6 e	1.9 de	4.7 de	94
Untreated reference	35.5 a	27.9 a	78.2 a	0

[1]Means in a column followed by the same letter are not statistically different according to a Fisher's Protected LSD test at a $P < 0.05$ level of significance.
[2]Analyses were conducted within weeks not across weeks; therefore, comparisons can only be made within a given column.

August 2009 and repeated again in 2010. Alligatorweed was obtained from a pond on the campus of Mississippi State University. Two stems, approximately 20 cm in length, were planted into each of 760, 4.2-L poly-cel bags containing a top soil, loam, and sand mixture. Soil was amended with 2 g L^{-1} (0.27 oz gal^{-1}) of Osmocote fertilizer[1] (24–8–16) to maintain growth throughout the 12-wk time span. Ten bags of planted alligatorweed (nine bags for three bags harvested at 4, 8, and 12 WAT and one bag for pretreatment harvest) were randomly placed by hand into each of the 76 mesocosm tanks. The mesocosm tanks are 90 cm in diameter and 45 cm deep. Four untreated control mesocosms were included for comparison. Water levels in each mesocosm were maintained at approximately 8 cm above the soil line. Plants were allowed 3 wk to acclimate and grow in their respective mesocosms prior to herbicide treatment. Coverage of alligatorweed in each mesocosm tank was $> 90\%$ at the time of herbicide application in order to mimic a dense infestation. A single pretreatment biomass sample was collected from every mesocosm on the day of herbicide application by removing one bag and cutting plant biomass at the sediment surface. Plants were dried for at least 7 d at 70 C and weighed for pretreatment biomass. Plant dry weights for each of the three individual bags harvested per mesocosm were averaged to obtain one weight per treatment at each biomass harvest date.

Foliar applications of the following herbicides at half maximum and maximum label rate recommendations, respectively, were made to the appropriate mesocosm: diquat[2] (2.24 and 4.48 kg ai ha^{-1}), glyphosate[3] (isopropylamine salt at 2.27 and 4.54 kg ae ha^{-1}), 2,4-D[4] (1.06 and 2.13 kg ae ha^{-1}), carfentrazone-ethyl[5] (0.11 and 0.22 kg ai ha^{-1}), penoxsulam[6] (0.05 and 0.101 kg ai ha^{-1}), imazamox[7] (0.28 and 0.56 kg ae ha^{-1}), imazapyr[8] (0.56 and 1.12 kg ae ha^{-1}), and triclopyr[9] (3.36 and 6.72 kg ae ha^{-1}). Herbicides were applied to plant foliage at a spray volume of 468 L ha^{-1} using a CO_2-pressurized, single-nozzle (8002 flat fan[10]) spray system.[11] A nonionic surfactant[12] was added to the spray solution at a rate of 0.5% v/v. All foliar herbicide treatments were randomly assigned to mesocosm tanks and replicated four times.

Four, eight, and twelve weeks after treatment (WAT), three bags were removed from each mesocosm and live plant material was harvested at the soil surface, dried for at least 7 d at 70 C, and weighed to determine plant biomass. A mixed effects model ANOVA procedure was developed using treatment as the main effect and year as a random effect to account for its influence on the results. Treatment effects were analyzed for each harvest (4, 8, and 12 WAT) separately. If a significant main effect was observed, means were separated by lsmeans and grouped using the LSD procedure. There was no significant "year" effect, so data was pooled for both years. Analyses were conducted within WAT at $\alpha = 0.05$ significance level.

RESULTS AND DISCUSSION

Pretreatment biomass was 7.54 g dry weight (DW) pot^{-1}, and by 12 WAT, the untreated control plant biomass had increased to 78.21 g DW pot^{-1} indicating plants were actively growing throughout the study. Both rates of carfentrazone-ethyl and the half maximum label rate of diquat provided the least control of alligatorweed as indicated by dry weight 12 WAT compared to all other herbicide treatments, though plant mass was different from untreated control plants (Table 1). Similarly, Richardson et al. (2008) reported limited control ($< 65\%$) of alligatorweed 4 WAT with a single application of carfentrazone-ethyl at rates up to 224 g ai ha^{-1} in a greenhouse evaluation. Glomski and Netherland (2007) also documented short-term control of variable-leaf milfoil (*Myriophyllum heterophyllum* Michx.) with an application of carfentrazone-ethyl at rates up to 200 µg ai L^{-1} but observed shoot regrowth as early as 15 DAT. Plant tissue regrowth is a common response to applications of contact herbicides such as carfentrazone-ethyl because of limited translocation within plants (Ross and Lembi 1985). Maximum rates of penoxsulam, glyphosate (IPA salt formulation), 2,4-D, triclopyr, imazamox, imazapyr, and diquat resulted in biomass reductions between 87% and 94%, but did not differ significantly 12 WAT between treatments with respect to dry weight (Table 1). Additionally, the half maximum label rates of 2,4-D, imazamox, glyphosate, imazapyr, penoxsulam, and triclopyr offered similar levels of control when compared to the maximum rates 12 WAT. Similar results were documented by Emerine et al. (2010) in that imazamox (560 g ae ha^{-1}) controlled alligatorweed 94% 5 WAT that was similar to applications of glyphosate (2,240 g ae ha^{-1}) and imazapyr (560 g ae ha^{-1}) based on visual observations and dry weight.

Contrary to results observed by Willingham et al. (2008) in which a limited efficacy of penoxsulam at 0.05 kg ai ha^{-1} was observed, penoxsulam applied at 0.05 kg ai ha^{-1} in the current study reduced alligatorweed dry weight by 70 to 80%, 4 to 12 WAT. Alligatorweed control with penoxsulam was also similar between rates.

Allen et al. (2007) reported that applications of imazapyr at rates of 0.29 to 1.04 kg ae ha^{-1} resulted in better control of alligatorweed when applied in spring than triclopyr applied at 1.73 to 5.18 kg ae ha^{-1}; though there was no significant difference in control between the herbicide treatments when applied in mid-summer of the same treatment year. Biomass is typically lower during spring months, suggesting that herbicide treatments should provide greater control when applied during this time (Willingham et al. 2008). Hofstra and Champion (2010) noted that a single application of triclopyr (6.5 kg ae ha^{-1}) controlled alligatorweed equivalent to imazapyr (0.48 kg ae ha^{-1}) with respect to dry weight 1 yr after treatment when young plants were treated. Imazapyr applied alone and in combination with glyphosate (1% v/v) or triclopyr (1.5% v/v) provided 65 to 88% 1 yr after treatment (YAT) (West et al. 2008).

In larger more mature populations (3 yr of growth), repeat applications of imazapyr (0.16 to 0.64 kg ai ha^{-1}) controlled alligatorweed significantly better than repeat applications of glyphosate (6.4 kg ae ha^{-1}) and triclopyr (6.5 kg ae ha^{-1}) approximately 1 yr after initial treatment (Hofstra and Champion 2010). Based on these studies, younger plants may be more susceptible because of less biomass, greater herbicide coverage, or these plants are more actively growing. Additionally, combination or repeat applications of imazapyr or imazapyr plus triclopyr or glyphosate may be necessary to achieve longer term control of larger alligatorweed infestations.

Our results suggest that foliar applications of the systemic herbicides evaluated in this study should provide similar control of alligatorweed resulting in $>$ 85% biomass reductions; however, field assessments are needed to verify control in natural populations. Rapid suppression can be achieved with lower rates of diquat, though significant regrowth can be expected by 12 WAT. Future work should evaluate treatment combinations with low use rates, herbicide timing with plant phenology, and developing an Integrated Pest Management strategy for alligatorweed management, including development of successful herbicide use patterns for long-term control.

SOURCES OF MATERIALS

[1]Osmocote fertilizer, Scotts-Sierra Horticultural Products Company, 14111 Scottslawn Road, Marysville, OH 43040.

[2]Diquat, Reward, Syngenta Professional Products, P.O. Box 18300, Greensboro, NC 27419.

[3]Glyphosate, Rodeo, Dow Agrosciences, 9330 Zionsville Road, Indianapolis, IN 46268.

[4]2,4-D, DMA 4-IVM, Dow Agrosciences, 9330 Zionsville Road, Indianapolis, IN 46268.

[5]Carfentrazone-ethyl, Stingray, FMC Corporation, 1735 Market Street, Philadelphia, PA 19103-7597.

[6]Penoxsulam, Galleon SC, SePRO Corporation, 11550 North Meridian Street, Carmel, IN 46032-4565.

[7]Imazamox, Clearcast, SePRO Corporation, 11550 North Meridian Street, Carmel, IN 46032-4565.

[8]Imazapyr, Habitat, BASF Corporation, 26 Davis Drive, Research Triangle Park, NC 27709.

[9]Triclopyr, Renovate 3, SePRO Corporation, 11550 North Meridian Street, Carmel, IN 46032-4565.

[10]8002 flat-fan nozzle, TeeJet Technologies, P.O. Box 7900, Wheaton, IL 60187-7901.

[11]CO_2 pressurized single nozzle spray system, R&D Sprayers, 419 Highway 104, Opelousas, LA 70570-2108.

[12]Non-ionic surfactant, Dyne-Amic, Helena Chemical Company, 225 Schilling Boulevard, Collierville, TN 38017-7177.

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