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Combinations of Penoxsulam and Diquat as Foliar Applications for Control of Waterhyacinth and Common Salvinia: Evidence of Herbicide Antagonism

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ABSTRACT

Waterhyacinth (*Eichhornia crassipes* [Mart.] Solms) and common salvinia (*Salvinia minima* Baker) are two floating aquatic plants that can cause wide-spread problems in the southern United States. These species can cause reductions in ecosystem function as well as the abundance of native plant species. Herbicides are often used in an attempt to control both species; however, few recommendations exist for common salvinia. Penoxsulam (2-(2,2-difluoroethoxy)-*N*-(5,8 dimethoxy [1,2,4] triazolo [1,5-*c*] pyrimidin-2-yl)-6 (trifluoromethyl) benzenesulfonamide) is newly registered for use in aquatic environments and is efficacious on floating plants as a submersed application; however, foliar application rates are largely undefined. The objectives of these studies were to determine the effect of foliar application rates of penoxsulam for waterhyacinth and common salvinia, and to evaluate the effectiveness of combinations of penoxsulam with diquat against these same plants species. A mesocosm study was conducted using foliar rates of penoxsulam (24.5, 49.1, and 98.2 g ai ha^{-1}) alone and in combination with diquat (130.8 g ai ha^{-1}). At six weeks after treatment (WAT), penoxsulam alone at all rates resulted in 100% control of waterhyacinth, and at 10 WAT control remained ≥90%. Penoxsulam was not as effective at controlling common salvinia. The combination of herbicides did not increase efficacy, and there was evidence of antagonism at the rates tested. Future studies should assess lower rates for waterhyacinth control and influences of salvinia mat thickness on application timing and herbicide efficacy.

Key words: Eichhornia crassipes, Galleon SC®, Reward®, *Salvinia minima*.

INTRODUCTION

Waterhyacinth (*Eichhornia crassipes* [Mart.] Solms) and common salvinia (*Salvinia minima* Baker) are widespread problems in waterways throughout the southern United States. Waterhyacinth is an invasive free-floating aquatic plant from the tropical and subtropical regions of South America (Holm et al. 1991). Waterhyacinth effectively doubles the number of plants within 12.5 d (Penfound and Earle 1948), increases dry biomass at a rate of 1.2% d^{-1}, and peak biomass can reach a maximum of 2.5 kg m^{-2} under optimal conditions (Center and Spencer 1981). Waterhyacinth impedes the recreational use of rivers and lakes (fishing, swimming, and boat traffic) and the generation of hydroelectric power. Furthermore, waterhyacinth increases the potential for flooding, reduces primary productivity (e.g., phytoplankton), and alters ecosystem properties (Toft et al. 2003).

Common salvinia is a free-floating aquatic fern native to central and South America (Olguin et al. 2002). While not as well known an invasive species as the congeneric giant salvinia (*Salvinia molesta* Mitchell), it is a significant nuisance weed in southern aquatic and wetland systems (Jacono and Richerson 2008). Common salvinia is capable of high growth rates and is tolerant to a wide range of environmental conditions (Olguin et al. 2002). In Louisiana, common salvinia biomass reached 1.02 kg m^{-2} and caused reductions in native plant abundance (Walley 2007).

To counteract the negative impacts often associated with non-native aquatic plants, effective control methods need to be identified. Penoxsulam (2-(2,2-difluoroethoxy)-*N*-(5,8 dimethoxy [1,2,4] triazolo [1,5-*c*] pyrimidin-2-yl)-6 (trifluoromethyl) benzenesulfonamide) was registered in 2008 for use in aquatic environments and may be effective in controlling non-native aquatic plants. Penoxsulam is an acetolactate synthase (ALS) inhibiting herbicide with a broad spectrum of grass and broadleaf weed control (Senseman 2007). Penoxsulam is readily absorbed by leaves, shoots, and roots, and is translocated to meristematic tissues via phloem and/or xylem flow (Senseman 2007). Susceptible plant injury usually results in rapid growth inhibition followed by chlorosis, vein reddening, and plant death within 4 weeks after treatment (WAT; Senseman 2007).

Penoxsulam is efficacious as a submersed application for control of waterhyacinth and giant salvinia at relatively low

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[3]Miracle-Gro® Water Soluable All Purpose Plant Food, The Scotts Company, P.O. Box 606 Marysville, OH 43040.

[4]Galleon SC®, SePRO Corporation, Carmel, Indiana.

[5]Reward® Landscape and Aquatic Herbicide, Syngenta Professional Products P.O. Box 18300 Greensboro, NC 27419.

[6]Sunwet®, Brewer International, P.O. Box 690037, Vero Beach, FL 32969. Received for publication August 16, 2009 and in revised form January 10, 2010.

use rates (ppb; Richardson and Gardner 2007), but foliar application rates for use as a spot treatment are largely undefined with no data available on common salvinia efficacy. Labeled rates of penoxsulam for control of floating species as a foliar application are 2 to 5.6 oz acre^{-1} (35.1 to 98.9 g ai ha^{-1}), with control taking up to 60 d or longer for some plant species (SePRO Corporation 2009). Therefore, combinations of penoxsulam with low or sublethal rates of a contact herbicide, such as diquat, may shorten the control period or provide rapid visual indication of exposure. The objectives of this study were to (1) determine foliar application rates of penoxsulam that are efficacious on waterhyacinth and common salvinia; and (2) evaluate whether tank mixing penoxsulam and diquat improves the speed and effectiveness of control for waterhyacinth and common salvinia.

MATERIALS AND METHODS

The study was conducted in 378-L mesocosms at the R. R. Foil Plant Science Research Center, Mississippi State University, for 10 weeks from August to November 2007. Waterhyacinth and common salvinia were planted from greenhouse stock at Mississippi State University by randomly placing each species into 24 mesocosms (48 mesocosms total) to cover the water surface. Plants were allowed to grow for approximately 2 weeks in respective mesocosms prior to herbicide applications. Mesocosms were amended with 30 mg L^{-1} of Miracle Gro®[3] fertilizer (24-8-16) weekly to maintain growth. A single pretreatment biomass sample was collected from every mesocosm the same day as herbicide applications using a 0.10 m^2 quadrat for waterhyacinth and a 0.05 m^2 quadrat for common salvinia.

Foliar applications of penoxsulam as Galleon® SC[4] were applied at 24.5, 49.1, and 98.2 g ai ha^{-1} (1.4, 2.8, 5.6 oz acre^{-1}) alone and in combination with diquat applied as Reward®[5] at 130.8 g ai ha^{-1} (4 oz acre^{-1}). All combination treatments were mixed in the same tank. A diquat-alone treatment was included as well as an untreated reference for statistical purposes. A 0.5% v:v methylated seed oil surfactant (Sunwet®[6]) was added to the spray solution, and the solutions applied at 935 L ha^{-1} using a CO_2 pressurized single nozzle (8002 flat fan) spray apparatus. Each treatment was replicated in 3 mesocosms. After herbicide application, mesocosms were immediately drained and refilled to remove any residual herbicide in the water. Plants were rated weekly for percent control on a scale of 0 (no control) to 100% (complete control) in 10% increments. At 6 and 10 WAT a single biomass sample was harvested in all waterhyacinth mesocosms using the 0.10 m^2 quadrat and two samples harvested in all common salvinia mesocosms using the 0.05 m^2 quadrat. The quadrats were placed into respective tanks and then live green plant material was harvested from within the quadrats.

A general linear model was used in SAS® to determine differences between control ratings within weeks, and a Fisher's Protected LSD was used to separate any differences. A similar analysis was conducted on biomass within species at 6 and 10 WAT. All analyses were conducted at a p = 0.05 level of significance.

Herbicide synergism or antagonism of penoxsulam and diquat was estimated using the dry weight biomass of waterhyacinth 10 WAT with the following equation outlined by Colby (1967):

$$E_1 = (X_1 + Y_1) - (X_1 Y_1 / 100) \qquad (1)$$

Waterhyacinth biomass was first converted to percent control prior to estimating herbicide response. In equation 1, E_1 is the expected control with herbicides A + B; X_1 is observed control with herbicide A; and Y_1 is control with herbicide B. When the observed plant response is greater than the expected response, the combination is synergistic; when less than expected the combination is antagonistic. When the observed and expected responses are equal the combination is considered additive. Observed and expected values were calculated for each replication (mesocosm) and values subjected to a Wilcoxin Rank Sum Test to determine statistical significance between the difference of the observed and expected values. Estimates were not computed for common salvinia due to rapid plant recovery in all treatments.

RESULTS AND DISCUSSION

Waterhyacinth

Visual waterhyacinth control was 65 to 70% at 1 WAT when applications included diquat, whereas control with penoxsulam alone was only 20 to 25% (Table 1). By 3 WAT, control was similar between the penoxsulam alone and combination treatments. All treatments that included penoxsulam were more effective than diquat alone treatments. At 4 WAT, the penoxsulam-alone treatments resulted in greater control than any treatment containing diquat. At 6 WAT, penoxsulam alone resulted in 100% control of waterhyacinth, and at 10 WAT control remained ≥90%. Applications containing diquat resulted in significant control early in the study when compared to untreated reference plants; however, there was significant antagonism between diquat and penoxsulam when used in combination (Table 2). By 8 WAT all combination treatments resulted in less control than penoxsulam alone.

Based on waterhyacinth biomass (Figure 1), there was significant antagonism between diquat and penoxsulam (Table 2). The penoxsulam alone treatments were more efficacious then the combination of penoxsulam + diquat and diquat alone. Cedergreen et al. (2007) reported that antagonism was the most common type of interaction between herbicides. Furthermore, the antagonistic response could be so severe that the effect of a single herbicide is reduced in the presence of the other herbicide. For example, the transport of the systemic herbicide glyphosate (N-(phosphonomethyl) glycine) was reduced when mixed with the photosystem II inhibitor terbuthylazine (N^2-*tert*-butyl-6-chloro-N^4-ethyl-1,3,5-triazine-2,4-diamine) (Cedergreen et al. 2007). Diquat also inhibited the translocation of glyphosate in the terrestrial plant *Phyllanthus tenellus* Roxb., where it was concluded diquat produced rapid visual symptoms but inhibited long

TABLE 1. CONTROL RATINGS OF WATERHYACINTH AND COMMON SALVINIA FOLLOWING FOLIAR APPLICATIONS OF PENOXSULAM AND DIQUAT ALONE AND IN COMBINATION.

Herbicide (g ai ha^{-1})		Weeks After Treatment[a]									
		One	Two	Three	Four	Five	Six	Seven	Eight	Nine	Ten
						%					
Waterhyacinth											
Untreated Reference		0 a	0 a	0 a	0 a	0 a	0 a	0 a	0 a	0 a	0 a
Penoxsulam 24.5		20 b	50 b	85 cd	90 e	100 d	100 d	100 e	100 e	100 f	100 e
Penoxsulam 49.1		25 b	50 b	80 c	90 e	95 d	100 d	100 e	90 de	90 ef	90 de
Penoxsulam 98.2		20 b	50 b	80 c	90 e	100 d	100 d	100 e	95 de	95 ef	95 de
Penoxsulam 24.5 + Diquat 130.8		70 c	70 c	70 c	70 c	70 c	60 bc	60 c	60 c	60 c	60 c
Penoxsulam 49.1 + Diquat 130.8		70 c	80 d	80 c	85 de	90 cd	90 bcd	85 de	80 d	80 ed	80 cd
Penoxsulam 98.2 + Diquat 130.8		70 c	70 c	80 c	80 d	80 c	70 bcd	70 cd	65 c	70 cd	70 c
Diquat 130.8		65 c	55 b	55 b	50 b	50 b	40 b	40 b	35 b	35 b	35b
	LSD	8	9	12	9	12	31	18	15	16	16
Common salvinia											
Untreated reference		0 a	0 a	0a	0 a	0 a	0 a	0 a	0 a	0 a	0 a
Penoxsulam 24.5		70 c	75 bc	70 bcd	65 c	60 c	30 ab	0 a	0 a	0 a	0 a
Penoxsulam 49.1		70 c	65 b	60 b	55 bc	45 bc	25 ab	0 a	0 a	0 a	0 a
Penoxsulam 98.2		80 c	90 bc	90 c	80 c	55 bc	30 ab	0 a	0 a	0 a	0 a
Penoxsulam 24.5 + Diquat 130.8		70 c	60 b	50 b	30 b	20 ab	5 a	0 a	0 a	0 a	0 a
Penoxsulam 49.1 + Diquat 130.8		80 c	80 bc	80 cd	80 c	70 c	45 b	20 a	20 a	0 a	0 a
Penoxsulam 98.2 + Diquat 130.8		70 c	70 bc	65 bc	60 bc	45 bc	15 ab	0 a	0 a	0 a	0 a
Diquat 130.8		25 b	5 a	0 a	0 a	0 a	0 a	0 a	0 a	0 a	0 a
	LSD	11	20	23	30	37	38	24	21		

[a]Means in a column followed by the same letter do not differ significantly at p = 0.05 according to Fisher's Protected LSD. Analyses were conducted within weeks and species.

TABLE 2. SYNERGISTIC OR ANTAGONISTIC RESPONSE OF WATERHYACINTH TO COMBINATIONS OF PENOXSULAM AND DIQUAT 10 WEEKS AFTER TREATMENT. AN ASTERISK INDICATES SIGNIFICANCE ACCORDING TO A WILCOXIN RANK SUM TEST.

Herbicide (g ai ha-1)	Observed Response (n = 3)	Expected Response	Difference in Response[a]
Biomass (% of Control)			
Penoxsulam 24.5 + Diquat 130.8	77	100	-23*
Penoxsulam 49.1 + Diquat 130.8	94	99	-5
Penoxsulam 98.2 + Diquat 130.8	90	100	-10*

[a]Calculated as the observed response - the expected response; a "+" represents synergism, and "-" represents antagonism from Colby (1967).

term control by glyphosate (Wehtje et al. 2008). Additionally, Wehtje stated higher glyphosate rates must be used to avoid loss of long-term efficacy in combination with diquat.

Our results show antagonism of diquat with all penoxsulam rates tested. The addition of diquat for control of waterhyacinth did not increase the efficacy of penoxsulam; excellent biomass reduction was achieved by 6 WAT with 24.5 g ai ha^{-} of penoxsulam and control maintained to 10 WAT. Because 24.5 g ai ha^{-1} was the lowest rate tested, additional tests should be conducted evaluating lower dose responses.

Common salvinia

Control of common salvinia was 70 to 80% 1 WAT for all applications with the exception of diquat alone (Table 1). By 2 WAT the 98.2 g ai ha^{-1} treatment of penoxsulam resulted in 90% control, however by 6 WAT control was only 30%. Control was similar between penoxsulam alone and the combination applications throughout the study with the exception of the 24.5 g ai ha^{-1} penoxsulam + diquat combination. This application resulted in less control by 2 WAT. Common salvinia had completely recovered by 7 WAT for all applications with the exception of diquat alone, which recovered by 3 WAT. Biomass collected at 6 and 10 WAT show significant reductions in common salvinia biomass when compared to reference plants (Figure 2). However, during both harvest times there were no distinct differences between applications with the exception of diquat alone. Biomass was similar in the diquat alone treatment and 24.5 g ai ha^{-1} penoxsulam + diquat by 10 WAT. This result with diquat alone was somewhat expected due to the low rate used. Nelson et al. (2001) reported that giant salvinia was very susceptible to diquat at rates of 2091 and 4182 g ai ha^{-1}, a >90% increase in diquat than that used in this study. Sublethal diquat rates were used in this

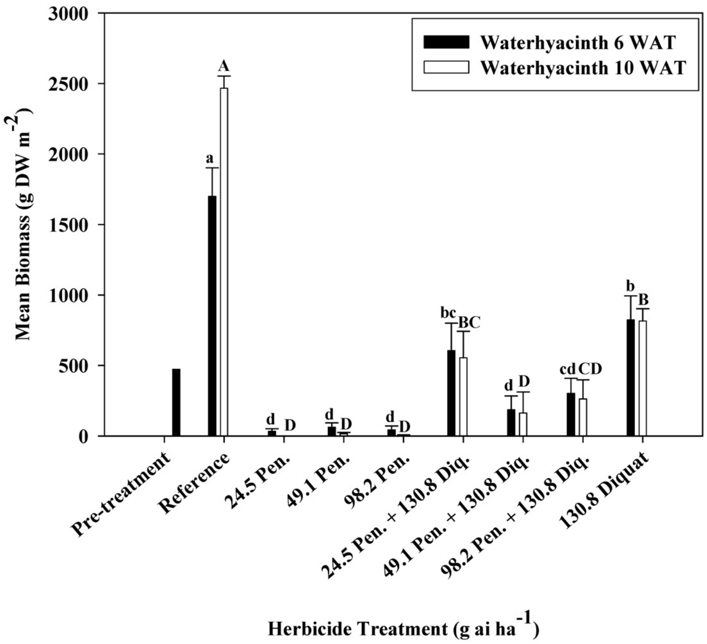

Figure 1. Mean (±1 SE) dry weight biomass of waterhyacinth harvested 6 and 10 WAT with penoxsulam and diquat. Bars sharing the same letter do not differ according to a Fisher's Protected LSD test at a p = 0.05 level of significance. All analyses were conducted within WAT; lower case letters compare means for 6 WAT, uppercase letters compare means at 10 WAT.

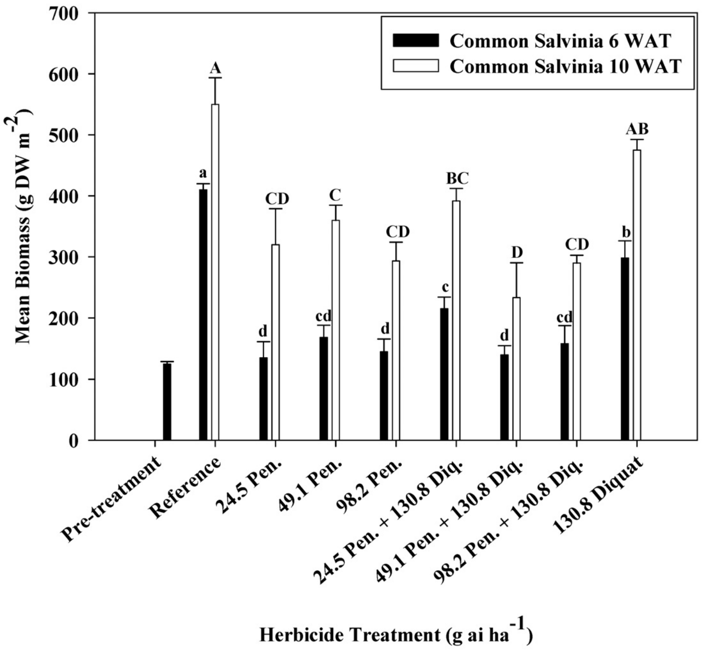

Figure 2. Mean (±1 SE) dry weight biomass of common salvinia harvested 6 and 10 WAT with penoxsulam and diquat. Bars sharing the same letter do not differ according to a Fisher's Protected LSD test at a p = 0.05 level of significance. All analyses were conducted within WAT; lower case letters compare means for 6 WAT, uppercase letters compare means at 10 WAT.

study to evaluate the potential to be used as a marker or enhance visual susceptibility of penoxsulam, or to enhance control.

Another explanation for reduced herbicide efficacy on salvinia may have been the thickness of the common salvinia mat at the time of application. Previous herbicide evaluations on giant salvinia were conducted on a single layer of plants (Nelson et al. 2001, 2007) or on individual plants (Fairchild et al. 2002). Mat thickness in the current study was 2 to 4 cm at the time of application. We speculate that plants at the surface of the mat were directly exposed to and killed by the herbicide. Plants under the surface mat did not come in contact with the spray solution and subsequently recolonized the mesocosms after the death of the exposed plants. This may explain the occasional failures of herbicide treatments on salvinia, duckweed, and watermeal under field conditions. Our data may be an indicator of herbicide efficacy on the mat phase of salvinia growth, although no research has been conducted on the direct effects of mat thickness on herbicide efficacy. We believe that having penoxsulam or diquat in the water column may result in better herbicide efficacy on salvinia species because more plants are in contact with the water.

These data show that penoxsulam applied as a foliar treatment is very efficacious on waterhyacinth. Control was achieved more rapidly, >90% 4 WAT, than the previously stated 60 days. Furthermore, greater control was achieved with penoxsulam alone at rates as low as 24.5 g ai ha^{-1} than by combining penoxsulam with diquat. Penoxsulam was not as effective at controlling common salvinia. The combination of penoxsulam with diquat did not offer any increased efficacy for either species; moreover, there was antagonism between these two herbicides. Future studies are needed to assess lower rates for waterhyacinth control and the influences of salvinia mat thickness on foliar application timing and herbicide efficacy. With the apparent susceptibility to penoxsulam, in-water treatments should also be further assessed for common salvinia as well as determining relationships between herbicide efficacy and salvinia mat thickness.

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