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Response of invasive floating plants and nontarget emergent plants to foliar applications of imazamox and penoxsulam

CHRISTOPHER R. MUDGE AND M. D. NETHERLAND*

ABSTRACT

The recently registered aquatic herbicides imazamox (2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid) and penoxsulam [2-(2,2-difluoroethoxy)-N-(5,8-dimethoxy[1,2,4]triazolo[1,5-c] pyrimidin-2-yl)-6-(trifluoromethyl) benzenesulfonamide] have demonstrated efficacy and selectivity to target and nontarget floating plants. Despite the high level of efficacy, these products are very slow to develop injury symptoms and require several weeks to control waterhyacinth [*Eichhornia crassipes* (Mart.) Solms] and waterlettuce (*Pistia stratiotes* L.). Therefore, a series of trials were conducted to determine if other aquatic herbicides or surfactants could be tank-mixed with the slow-acting herbicides to provide rapid visual injury symptoms and rapid control to waterhyacinth and waterlettuce. In the floating-target trials, a low rate of imazamox and penoxsulam alone and combination treatments with carfentrazone (ethyl α,2-dichloro-5-[4-(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1H-1,2,4-triazol-1-yl]-4-fluorobenzenepropanoate) or 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) reduced waterhyacinth dry weight 30 to 69% 8 wk after treatment (WAT), whereas all treatments, except imazamox alone, provided 47 to 72% waterlettuce control. Waterhyacinth injury was noticeable 10 d after treatment (DAT) when treated with penoxsulam and imazamox alone, whereas the addition of a contact herbicide or two surfactant mixture provided a visual marker by 4 or 7 DAT, respectively. On the other hand, waterlettuce responded similarly to the acetolactate synthase–inhibiting herbicides when applied alone, and the addition of flumioxazin or carfentrazone resulted in injury symptoms 2 or 3 DAT, respectively. The low dose alone and combination foliar treatments were also evaluated for selectivity against lanceleaf arrowhead (*Sagittaria lancifolia* L.), jointed spikerush [*Eleocharis interstincta* (Vahl) Roem & J.A. Schult], gulfcoast spikerush (*Eleocharis cellulosa* Torr.), California bulrush [hard-stem bulrush, *Schoenoplectus californicus* (C.A. Mey) Palla], and softstem bulrush [*Schoenoplectus tabernaemontani* (K.C. Gmel.) Palla]. The herbicide treatments containing imazamox or penoxsulam alone or in combination with contact herbicides resulted in minimal injury to gulfcoast spikerush [*Eleocharis interstincta* (Vahl) Roem & J.A. Schult], California bulrush, and softstem bulrush [*Schoenoplectus tabernaemontani* (K.C. Gmel.) Palla], whereas these treatments were injurious to varying degrees to lanceleaf arrowhead and jointed spikerush 6 WAT. These results indicate imazamox and penoxsulam alone or in combination with contact herbicides may be suitable for selectively managing waterhyacinth and waterlettuce.

Key words: 2,4-D, acetolactate synthase inhibitors, carfentrazone-ethyl, chemical control, diquat, *Eichhornia crassipes*, *Eleocharis cellulose*, *Eleocharis interstincta*, endothall, flumioxazin, *Pistia stratiotes*, protoporphyrinogen oxidase inhibitor, *Sagittaria lancifolia*, *Schoenoplectus californicus*, *Schoenoplectus tabernaemontani*, selectivity, surfactant, tank mix.

INTRODUCTION

Waterhyacinth [*Eichhornia crassipes* (Mart.) Solms] and waterlettuce (*Pistia stratiotes* L.) are widespread problems in waterways throughout Florida and other southern U.S. states. These floating invasive plants spread via vegetative reproduction forming extensive free floating mats, which often interfere with navigation, hydroelectric generation, irrigation, and fishing and which also lowere the dissolved oxygen and pH of the water (Weldon and Blackburn 1966; Harley et al. 1984; Owens and Madsen 1995). The plants may also harbor mosquitoes, which are vectors for diseases such as dengue fever, malaria, and encephalitis (Holm et al. 1977). Experience in Florida has demonstrated that consistent herbicide management to keep floating plants under maintenance control is the best available technology (Schmitz et al. 1993; University of Florida 2012b). When these techniques are used in a coordinated manner, on a continuous or periodic basis, the target plant population is maintained at the lowest feasible level that funding and technology will permit (Florida Fish and Wildlife Conservation Commission 2012).

The herbicides diquat [6,7-dihydrodipyridol (1,2-α:2′,1′-c) pyrazinediium ion] and 2,4-D [(2,4-dichlorophenoxy)acetic acid] are the most widely used for waterlettuce and waterhyacinth control; however, the nonselective products glyphosate [N-(phosphonomethyl)glycine] and imazapyr [(±)-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1-*H*-imidazol-2-yl]-3-pyridinecarboxylic acid], and the auxin

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mimic triclopyr ([(3,5,6-trichloro-2-pyridinyl)oxy]acetic acid) are also recognized as efficacious against these floating invasive plants (Langeland et al. 2009). In Louisiana alone, 2,4-D is used to treat between 30,000 and 60,000 ha of waterhyacinth annually (Sanders et al. 2010). Aquatic herbicide applicators managing large water bodies in Florida have become accustomed to rapid symptoms and fast plant death associated with diquat and 2,4-D. These herbicides not only provide quick control, but offer rapid visual markers (hours to 1 d), which help distinguish treated versus untreated sites. Although these visual cues have been important to the maintenance control program, visual injury symptoms to nontarget vegetation is becoming increasingly scrutinized by stakeholder groups. Although 2,4-D and diquat have been the mainstays of floating plant management programs in Florida for the past several decades (University of Florida 2012a) increasing pressure from stakeholder groups regarding nontarget impacts on emergent plants has led to greater consideration of alternate herbicides. For example, the Florida Fish and Wildlife Conservation Commission recommends not using 2,4-D when controlling mixed plant communities of waterhyacinth and nontarget vegetation due to significant injury or control of members of the bulrush (*Schoenoplectus* spp.) family (i.e. California bulrush [*Schoenoplectus californicus* (C.A. Mey) Palla], softstem bulrush [*Schoenoplectus tabernaemontani* (K.C. Gmel.) Palla]) (University of Florida 2011).

The recently registered acetolactate synthase (ALS)–inhibiting herbicides imazamox (2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid) and penoxsulam [2-(2,2-difluoroethoxy)-N-(5,8-dimethoxy [1,2,4]triazolo[1,5-c] pyrimidin-2-yl)-6-(trifluoromethyl) benzenesulfonamide] are also efficacious against both waterhyacinth and waterlettuce at low use rates (grams of active ingredient per hectare) (Emerine et al. 2010; Wersal and Madesen 2010). Penoxsulam is labeled for control of floating species at 35.1 to 98.9 g ai ha^{-1}, with control taking up to 60 d or longer (Senseman 2007, SePRO Corporation 2009). Wersal and Madsen (2010) found that penoxsulam applied as low as 24.5 g ai ha^{-1} reduced waterhyacinth biomass $> 90\%$ by 10 wk after treatment (WAT). However, this low-dose stand-alone treatment provided only 20% phytotoxicity to waterhyacinth at 1 WAT. Similar results were noted when Mudge and Netherland (unpublished data) demonstrated that penoxsulam provided 81 to 98% waterhyacinth control and imazamox controlled waterhyacinth 79 to 97%. Both herbicides provided 61 to 97% waterlettuce control (Mudge and Netherland, unpublished data). Netherland (2011) noted that the slow development of injury symptoms and time required to achieve control of floating vegetation with ALS herbicides would result in a challenge in incorporating these products into current and traditional maintenance control programs. The slow activity of the ALS inhibitors may be problematic for aquatic managers who have come to utilize visual markers (1 DAT) and expect rapid control associated with 2,4-D and diquat treatments.

Applying a combination of contact herbicides with slow-acting, systemic herbicides may decrease the time for visual symptoms to appear and/or increase the efficacy of the herbicide treatment. However, limited data exist to determine if these combinations will provide effective control of floating plants while reducing nontarget injury. To address questions regarding compatibility, efficacy, and selectivity of product mixtures, mesocosm trials were conducted to 1) determine if the addition of low foliar application rates of contact herbicides or surfactants will improve the speed or efficacy of imazamox and penoxsulam when applied to waterhyacinth and waterlettuce and 2) determine the selectivity of these combination treatments against five key nontarget emergent species.

MATERIALS AND METHODS

Target floating plants combination experiment

The waterhyacinth experiment was conducted at the U.S. Army Engineer Research and Development Center (USAERDC) in Vicksburg, MS, in outdoor mesocosms to determine the efficacy of imazamox and penoxsulam plus contact herbicides or surfactants. On 30 June 2011, eight waterhyacinth plants (18 to 22 cm in height) obtained from Saline Lake, in Louisiana, were placed in individual 76-L plastic containers (ca. 49.5 cm diam by 58.4 cm height) cultured outdoors under full sunlight. The containers were filled with tap water that was amended with Miracle-Gro®[1] (36–6–6) at a rate of 41.6 mg L^{-1}. The fertilizer was added to the experimental units every 4 wk throughout the course of the experiment. The plastic containers were placed inside larger plastic tanks (946 L) partially filled with water, which served as a water bath to help maintain a consistent water temperature.

Three weeks after study inception (21 July 2011), waterhyacinth plants received low foliar application rates (7 to 36% of maximum label rate) of imazamox[2] or penoxsulam[3] alone or in combination with carfentrazone-ethyl[4] [(ethyl α,2-dichloro-5-[4-(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1*H*-1,2,4-triazol-1-yl]-4-fluorobenzenepropanoate), hereinafter referred to as carfentrazone], flumioxazin[5] (2-[7-fluoro-3,4-dihydro-3-oxo-4-(2-propynyl)-2H-1,4-benzoxazin-6-yl]-4,5,6,7-tetrahydro-1*H*-isoindole-1,3(2H)-dione), or a mixture of two surfactants[6,7] (Table 1). All herbicide treatments, except the treatments containing two surfactants, included one surfactant[8] (methylated vegetable oil plus organosilicone). The two-surfactant mixture consisted of (1) spreader-activator with buffering agents and (2) nonionic organosilicone surfactant. The two-surfactant mixture is commonly used with diquat and glyphosate to control giant salvinia (*Salvinia molesta* D. S. Mitchell) in Louisiana and Texas (Mudge et al. 2012). Herbicide treatments were applied to waterhyacinth using a forced air CO_2-powered sprayer calibrated to deliver 935 L ha^{-1} diluent through a single TeeJet®[9] 80-0067 nozzle. A nontreated control was included for comparison. This study was a completely randomized design and treatments were replicated four times.

Visual estimates of waterhyacinth injury were recorded every day for the first 2 wk and weekly thereafter to determine speed and long-term effectiveness of herbicide treatments. Injury was recorded when $\geq 10\%$ of the plant material in a particular treatment showed visual damage. At

TABLE 1. FOLIAR HERBICIDE AND HERBICIDE COMBINATION TREATMENTS APPLIED TO FLOATING TARGET AND EMERGENT NONTARGET AQUATIC PLANT SPECIES IN THE HERBICIDE COMBINATION EXPERIMENTS IN VICKSBURG, MS.

Herbicide treatment	Rate (g ai h$-^{1}$)[a]	Experiment
Imazamox + surfactant[b]	70.1 + 1.0% v/v	Floating, emergent
Imazamox + carfentrazone + surfactant	70.1 + 16.6 + 1.0% v/v	Floating, emergent
Imazamox + endothall[c] + surfactant	70.1 + 37.1 + 1.0% v/v	Emergent
Imazamox + flumioxazin + surfactant	70.1 + 17.9 + 1.0% v/v	Floating, emergent
Imazamox + two surfactants[c]	70.1 + 1.0% v/v + 0.5% v/v	Floating
Penoxsulam + surfactant	35.0 + 1.0% v/v	Floating, emergent
Penoxsulam + carfentrazone + surfactant	35.0 + 16.6 + 1.0% v/v	Floating, emergent
Penoxsulam + endothall[c] + surfactant	35.0 + 37.1 + 1.0% v/v	Emergent
Penoxsulam + flumioxazin + surfactant	35.0 + 17.9 + 1.0% v/v	Floating, emergent
Penoxsulam + two surfactants[c]	35.0 + 1.0% v/v + 0.5% v/v	Floating
2,4-D + surfactant	2130.6 + 1.0% v/v	Emergent
2,4-D + diquat + surfactant	1065.3 + 560.7 + 1.0% v/v	Emergent

[a] Endothall and 2,4-D were applied as g ae ha^{-1}.

[b] Surfactant: methylated vegetable oil plus organosilicone.

[c] Two surfactants: spreader-activator with buffering agents + nonionic organosilicone.

8 WAT, all living waterhyacinth biomass was harvested, dried to a constant weight (70 C for 2 wk), and recorded as dry weight. Dry weight data were subjected to ANOVA and means were separated using Fisher's Protected LSD test ($P=0.05$). Since waterhyacinth biomass data did not meet assumption of normality, data were transformed using a plus-1 transformation.

Twelve waterlettuce plants (10 to 12 cm in diam) were utilized in a manner similar to the waterhyacinth experiment. Plants collected from the Center for Aquatic and Invasive Plants, University of Florida (Gainesville, FL) were established on 5 July 5 2011 and treated 4 wk after establishment (9 August 2011). All herbicide treatments, rates, and procedures were the same in as the waterhyacinth experiment. At 8 WAT (6 October 2011), all living waterlettuce biomass was harvested, dried to a constant weight (70 C for 2 wk), and recorded as dry weight biomass. Dry weight data were subjected to ANOVA and means were separated using Fisher's Protected LSD test ($P=0.05$).

Nontarget emergent plants combination experiment

The sensitivity of the nontarget emergent species lanceleaf arrowhead (*Sagittaria lancifolia* L.), jointed spikerush [*Eleocharis interstincta* (Vahl) Roem & J.A. Schult], gulfcoast spikerush (*Eleocharis cellulosa* Torr.), California bulrush, and softstem bulrush were evaluated against foliar applications of imazamox and penoxsulam combinations in two experiments. All plants were purchased from a Florida plant nursery and shipped overnight to USAERDC. The initial and repeated studies were planted on 25 April 2012 and 2 May 2012, respectively. One healthy plant propagule (30 to 40 cm) of each species was planted in a mixture of 2 : 1 topsoil : masonry sand in 3-L high-density polyethylene pots amended with Osmocote®[10] (19-6-12) fertilizer at a rate of 2 g kg^{-1} soil. The experiments were randomized with four replicates each. One pot of each species (five total pots) was placed inside 76-L plastic containers (49.5 cm diam by 58.4 cm height) cultured outdoors under full sunlight. To acclimate the plants, water level was maintained at 20 cm for 4 wk and raised to 38 cm for the remainder of the study. The plastic containers were placed inside larger plastic tanks (946 L) partially filled with water to help maintain a consistent water temperature.

Plants were cultured for 8 wk and foliar herbicide treatments were applied using the same methods as the floating plant experiments. Similar herbicide treatments were evaluated against the nontarget emergent plants (Table 1). The two-surfactant-plus-herbicide mix was eliminated. In addition, combinations of the dipotassium salt formulation of endothall[11] (7-oxabicyclo[2.2.1] heptane-2,3-dicarboxylic acid) plus imazamox or penoxsulam as well as 2,4-D[12] and 2,4-D plus diquat[13] were evaluated. The 2,4-D and 2,4-D plus diquat treatments are commonly used to control waterlettuce and waterhyacinth in Florida and are often nonselective to many of the nontargets used in this experiment. Similar to the target floating trial, plant injury was noted throughout the course of the emergent experiments.

On 31 July and 7 August 2012 (6 WAT), all live shoot tissue was harvested at the soil line, placed in a drying oven at 70 C for 2 wk, and weighed. Jointed spikerush, gulfcoast spikerush, California bulrush, and softstem bulrush dry weight data were subjected to ANOVA and means were separated using Fisher's Protected LSD test ($P=0.05$). Data were pooled across experimental runs for all species because a treatment by trial interaction was not detected. Lanceleaf arrowhead data failed normality and equal variance assumptions and were analyzed by Kruskal-Wallis one-way ANOVA on ranks and means separated by the Student-Newman-Keuls method.

RESULTS AND DISCUSSION

Target floating plants combination experiment

The purpose of the combination experiments was to determine if tank-mix additives were compatible and if contact herbicides or a two-surfactant mixture could increase the rate of control or provide immediate visual markers. All foliar-applied individual or combination imazamox and penoxsulam treatments resulted in injury symptoms 2 to 10 DAT for both waterhyacinth and waterlettuce (Table 2). Plants treated with the systemic

Table 2. Days to 10% or greater visual injury of floating target and emergent nontarget aquatic plant species treated with foliar herbicide and herbicide combination treatments.

	Floating target plants		Emergent nontarget plants				
Treatment	Waterhyacinth	Waterlettuce	Lanceleaf arrowhead	Jointed spikerush	Gulfcoast spikerush	California bulrush	Softstem bulrush
I + S[a,b]	10[c]	7	14	0	—	0	0
I + C + S	4	3	7	14	0	0	0
I + E[d] + S	N/A	—	7	14	14	0	14
I + F + S	4	2	7	0	0	7	7
I + 2 S	7	7	—	—	—	—	—
P + S	10	7	7	0	0	0	0
P + C + S	4	3	7	14	0	14	14
P + E[d] + S	—	—	7	14	14	14	14
P + F + S	4	2	7	14	0	7	7
P + 2 S	7	7	—	—	—	—	—
2,4-D + S	—	—	3	3	3	3	3
2,4-D + D + S	—	—	1	1	1	1	1

[a] Abbreviations: I, imazamox; P, penoxsulam; C, carfentrazone; E, endothall; F, flumioxazin; S, surfactant; D, diquat.

[b] Herbicide (g ai ha–1) and surfactant application rates: I, 70.1; P, 35.0; C,16.6; E, 37.1; F, 17.9; S, 1.0% v/v; 2 S, 1% v/v plus 0.5% v/v; 2,4-D, 2,130.6 (alone) and 1,065.3 (combination with D); D, 560.7.

[c] Injury indicates number of days until injury was $\geq$ 10%; N/A indicates that the herbicide was not applied to the given plant species; — indicates that plant injury never exceeded 10%.

[d] Endothall and 2,4-D were applied as g ae ha^{-1}.

ALS herbicides imazamox and penoxsulam alone were slow in developing injury symptoms compared to plants receiving combinations with carfentrazone or flumioxazin. Initially, the ALS herbicides alone or plus a two-surfactant mixture growth-regulated or stunted waterlettuce, whereas all combination treatments with carfentrazone or flumioxazin resulted in necrosis and chlorosis. Penoxsulam and imazamox alone required 10 d to develop injury symptoms on waterhyacinth, whereas the addition of a contact herbicide or two-surfactant mixture provided a visual marker by 4 or 7 DAT, respectively. Waterlettuce plants responded similarly to the ALS herbicides when applied alone or with the surfactant mixture, whereas the addition of flumioxazin or carfentrazone resulted in injury symptoms 2 or 3 DAT, respectively. The sensitivity of waterlettuce to flumioxazin compared to waterhyacinth was demonstrated in mesocosm research by Mudge and Haller (2012). These data indicate that low rates of imazamox or penoxsulam alone may be suitable only if next-day visual markers are not necessary.

All individual or combination imazamox and penoxsulam treatments reduced waterhyacinth dry weight 30 to 69% compared to the nontreated control 8 WAT (Figure 1). There was no benefit to tank-mixing carfentrazone, flumioxazin, or the two-surfactant mixture to imazamox or adding the surfactant combination to penoxsulam. However, the addition of a second herbicide was beneficial for penoxsulam compared to imazamox. Also, penoxsulam plus carfentrazone and penoxsulam plus flumioxazin were the only other treatments that reduced biomass at or near pretreatment level.

Seven of the nine individual or combination herbicide treatments evaluated in the waterlettuce experiment were efficacious (Figure 1). Imazamox alone was the only treatment that did not provide control or reduce plant dry weight to below pretreatment level. Although all treated waterlettuce plants exhibited necrosis and chlorosis 2 to 7 DAT, regrowth of young plants (ramets) was noted in all tanks by 2 or 3 WAT. The addition of carfentrazone or flumioxazin to imazamox and penoxsulam resulted in 63 to 72% control. Future research should be conducted to determine if higher application rates of either systemic or contact herbicides can increase the speed of injury and control of waterhyacinth or waterlettuce.

Herbicide combinations have been evaluated for control of aquatic plants in previous research. For example, after evaluating various treatment strategies in Louisiana, a mixture of glyphosate (3.4 kg ae ha^{-1}), a low rate of diquat (210.3 to 280 g ai ha^{-1}), and two surfactants (spreader-activator with buffering agents and nonionic organosilicone) is currently the most economical and effective foliar treatment for control of the floating plant giant salvinia (D. E. Sanders, pers. comm.). However, research by Wersal and Madsen (2010) demonstrated the addition of 130.8 g ai ha^{-1} diquat to penoxsulam reduced efficacy and there was evidence of antagonism with the combination.

In the current experiment, limited additional control was achieved by the addition of another product to imazamox or penoxsulam. However, despite the limited control, injury symptoms were more visibly noticeable and intense on waterhyacinth and waterlettuce 1 WAT when carfentrazone, flumioxazin, or the two-surfactant mixture were added to the spray solution compared to the ALS herbicides applied with only one surfactant. In addition, the plants were mature at the time of treatment; immature plants may be more susceptible to the herbicides and herbicide combinations.

The direct focus of this research was not to determine if the combinations could provide control, but to determine if the herbicides were compatible and provide rapid visual markers. These results indicate that all combinations were compatible and control wasn't significantly decreased when imazamox or penoxsulam were applied with either carfentrazone or flumioxazin. Future studies will evaluate higher foliar rates of penoxsulam and imazamox or the tank-mix partner to determine if faster injury symptoms, decreased regrowth, and better overall control can be achieved. In addition, future research will evaluate other systemic or

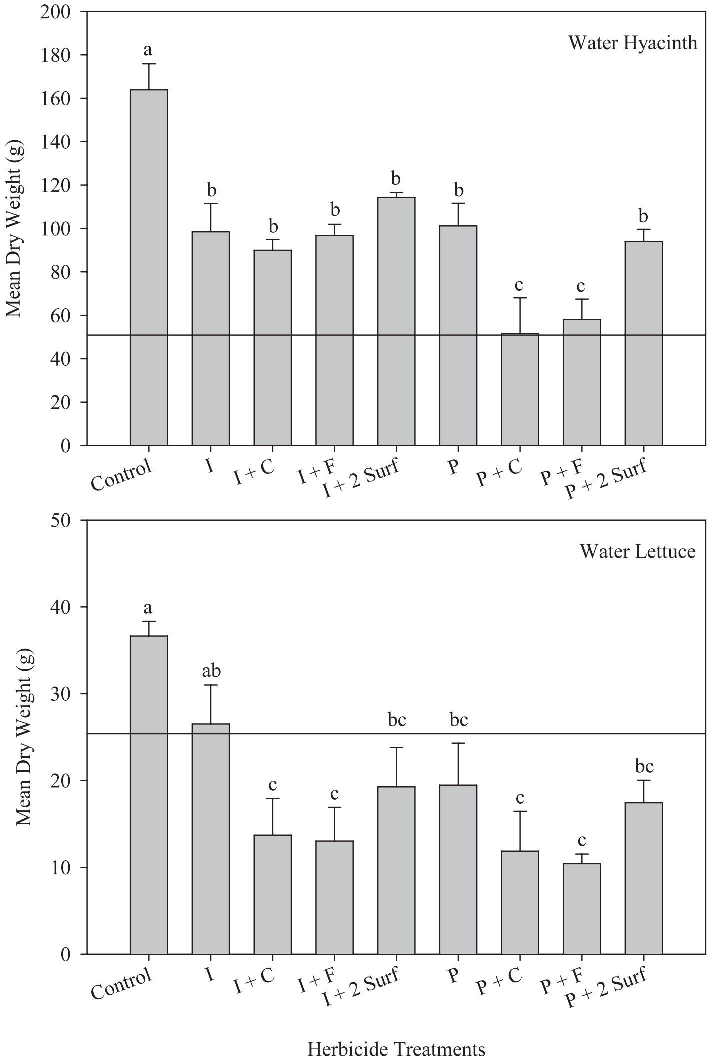

Figure 1. Effect of low-dose foliar application rates (g ai ha^{-1}) of imazamox (I, 70.1) or penoxsulam (P, 35.0) alone and in combination with carfentrazone (C, 16.6), or flumioxazin (F, 17.9), or two surfactants (Surf, spread-activator with buffering agents and nonionic organosilicone) on waterhyacinth and waterlettuce dry weight (mean ± SE) 8 wk after treatment. A methylated vegetable oil plus organosilicone surfactant was added to all treatments except the two-surfactant treatment. Means with the same letter are not significant according to Fisher's Protected LSD test at $P = 0.05$; $n = 4$. Horizontal line represents pretreatment biomass.

contact tank-mix partners for compatibility. Smaller or immature waterhyacinth and waterlettuce plants should also be tested for susceptibility to these treatments.

Nontarget emergent plants experiment

Alone and in combination, treatments containing imazamox or penoxsulam resulted in noticeable injury symptoms to most nontarget emergent plants 7 to 14 DAT (Table 2). Injury symptoms were similar to those noted in the floating-target experiments. Temporary growth regulation or stunting as well as minor necrosis and chlorosis ($< 25\%$ injury) was existent on the bulrush and spikerush species treated with ALS herbicides and ALS plus contact herbicide combinations. Severe necrosis and chlorosis was viewed on all plants treated with 2,4-D and 2,4-D plus diquat, with 25 to 60% and 35 to 85% visual injury 1 WAT and 2 WAT, respectively. Lanceleaf arrowhead was the only emergent species that was visually injured by all herbicide treatments as well as being extremely sensitive to penoxsulam alone and combination treatments. Three of the four penoxsulam alone and combination penoxsulam treatments resulted in 83 to 100% lanceleaf arrowhead control and no plant regrowth (Figure 2). The 2,4-D and 2,4-D plus diquat treatments resulted in plant injury 3 and 1 DAT, respectively (Table 2). Lanceleaf arrowhead and jointed spikerush recovery was 7 and 14 d faster, respectively, than plants treated with the imazamox and penoxsulam combinations. Conversely, plant recovery did not occur until 28 DAT for gulfcoast spikerush, California bulrush, and softstem bulrush when treated with either 2,4-D or 2,4-D plus diquat.

The herbicide treatments containing imazamox, penoxsulam alone, or penoxsulam in combination with contact herbicides did not reduce biomass of gulfcoast spikerush (data not shown), California bulrush, or softstem bulrush, whereas these treatments were injurious to varying degrees to lanceleaf arrowhead and jointed spikerush 6 WAT (Figure 2). The only treatments to impact California bulrush were 2,4-D and 2,4-D plus diquat, which was anticipated since these treatments are nonselective to California bulrush (University of Florida 2011). Lanceleaf arrowhead biomass was reduced 46 to 100% by imazamox plus flumioxazin, all penoxsulam treatments, and 2,4-D. This nontarget emergent species was more susceptible to penoxsulam alone and penoxsulam combination treatments compared to imazamox alone or imazamox combination treatments. Previous research (Koschnick et al. 2007) demonstrated similar results when subsurface applications of penoxsulam were more injurious to lanceleaf arrowhead than imazamox.

Penoxsulam plus endothall was the only treatment besides 2,4-D and 2,4-D plus diquat that reduced jointed spikerush dry weight (30%). However, this reduction was minimal and plant dry weight was well above pretreatment level. Use of 2,4-D alone (2.1 kg ae ha^{-1}) reduced the dry weight of all emergent nontarget plants except gulfcoast spikerush 72 to 94% of the nontreated control 6 WAT. The combination treatment is commonly used to control mixed populations of waterhyacinth and waterlettuce in Florida (J. M. Crossland, pers. comm.) because of the broad spectrum provided by these products when used together. In this study, the lower rate of 2,4-D (1.06 vs. 2.1 kg ae ha^{-1}) in combination with diquat (560.7 g ai ha^{-1}) provided more selectivity to lanceleaf arrowhead and jointed spikerush than 2,4-D alone.

Many of the combination treatments provided faster visual markers on waterhyacinth and waterlettuce compared to imazamox and penoxsulam alone. In general, the treatments failed to provide the rapid injury desired by aquatic herbicide applicators that rely on next-day visual markers to determine where to continue spraying the day following initial treatment. The slow activity may be negated by the use of a global positioning system to identify where previous herbicide applications have occurred. In addition,

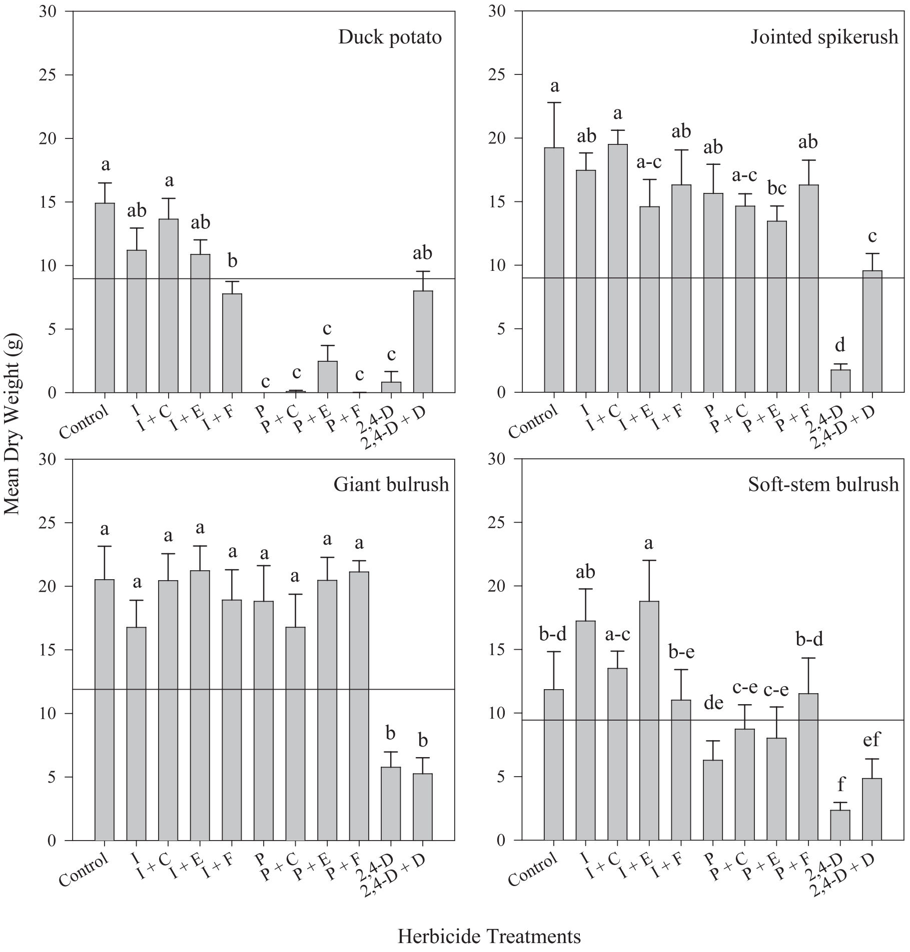

Figure 2. Effect of low-dose foliar application rates (g ai ha^{-1}) of imazamox (I, 70.1) or penoxsulam (P, 35.0) alone and combination with carfentrazone (C, 16.6), endothall (E, 37.1), or flumioxazin (F, 17.9) as well as 2,4-D (2.1) and 2,4-D (1.06) plus diquat (D, 560.7) on lanceleaf arrowhead, jointed spikerush, California bulrush, and softstem bulrush shoot dry weight (mean ± SE) 6 wk after treatment. Endothall was applied as g ae ha^{-1} and 2,4-D as kg ae ha^{-1}. A methylated vegetable oil plus organosilicone surfactant (1% v/v) was added to all treatments. Means with the same letter are not significant according to Fisher's Protected LSD test at $P = 0.05$ for all species except lanceleaf arrowhead. Lanceleaf arrowhead data were analyzed by Kruskal-Wallis one-way ANOVA on ranks and means were separated by the Student-Newman-Keuls method; $n = 8$. Horizontal line represents pretreatment biomass.

research should be conducted to determine if dyes can be mixed with the herbicides to determine compatibility and how long the dyes can provide visual markers before plants begin to display injury symptoms. Conversely, the majority of the treatments evaluated against the five ecologically important emergent plants showed evidence of selectivity. As higher rates of ALS herbicides and tank-mix partners will be required for waterhyacinth and waterlettuce control, further evaluations against the nontarget emergent species are recommended.

SOURCES OF MATERIALS

[1] Miracle-Gro® Lawn Fertilizer, The Scotts Company, P.O. Box 606, Marysville, OH 43040.

[2] Clearcast®, SePRO Corporation, 11550 North Meridian Street, Suite 600, Carmel, IN 46032.

[3] Galleon®, SePRO Corporation, 11550 North Meridian Street, Suite 600, Carmel, IN 46032.

[4] Stingray™, FMC Corporation, 1735 Market Street, Philadelphia, PA 19103.

[5] Clipper™ herbicide, Valent USA Corporation, P.O. Box 8025, Walnut Creek, CA 94596.

[6] Aqua-King Plus®, Winfield Solutions LLC, P.O. Box 64589, St. Paul, MN 55164.

[7] Thoroughbred®, Winfield Solutions LLC, P.O. Box 64589, St. Paul, MN 55164.

[8] Inergy®, Winfield Solutions LLC, P.O. Box 64589, St. Paul, MN 55164.

[9] TeeJet®, Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60187.

[10] Osmocote®, The Scotts Company, P.O. Box 606, Marysville, OH 43040.

[11] Aquathol® K, United Phosphorus, Inc., 630 Freedom Business Center, Suite 402, King of Prussia, PA 19406.

[12] DMA® 4 IVM, Dow AgroSciences LLC, 9330 Zionsville Road, Indianapolis, IN 46268.

[13] Reward® Landscape and Aquatic Herbicide, Syngenta Professional Products, P.O. Box 18300, Greensboro, NC 24719.

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LITERATURE CITED

Emerine SE, Richardson RJ, True SL, West AM, Roten RL. 2010. Greenhouse response of six aquatic invasive weeds to imazamox. J. Aquat. Plant Manag. 48:105–111.

Florida Fish and Wildlife Conservation Commission. 2012. Aquatic Plant Permit Rules. http://myfwc.com/license/aquatic-plants/permit-rules/. Accessed April 15, 2013.

Harley KLS, Forno IW, Kassulke RC, Sands DPA. 1984. Biological control of water lettuce. J. Aquat. Plant Manag. 22:101–102.

Holm LG, Plucknett DL, Pancho JV, Herberger JP. 1977. The World's Worst Weeds: Distribution and Biology. 18th ed. Univ. Press, Honolulu, HI. 609 pp.

Koschnick TJ, Netherland MD, Haller WT. 2007. Effects of three ALS-inhibitors on five emergent native plant species in Florida. J. Aquat. Plant Manag. 45:47–51.

Langeland K, Netherland M, Haller W. 2009. Efficacy of Herbicide Active Ingredients Against Aquatic Weeds. University of Florida, Institute of Food and Agricultural Sciences. http://edis.ifas.ufl.edu/ag262. Accessed April 15, 2013.

Mudge CR, Haller WT. 2012. Response of target and non-target floating and emergent aquatic plants to flumioxazin. J. Aquat. Plant Manag. 50:111–116.

Mudge CR, Heilman MA, Theel HJ, Getsinger KD. 2012. Efficacy of subsurface and foliar penoxsulam and fluridone applications on giant salvinia. J. Aquat. Plant Manag. 50:116–124.

Netherland MD. 2011. Selective Control of Water Hyacinth and Water Lettuce Growing Among Bulrush. http://apms.org/wp/wp-content/uploads/2012/10/2011program1.pdf. Accessed April 16, 2013.

Owens CS, Madsen JD. 1995. Low temperature limits of water hyacinth. J. Aquat. Plant Manag. 33:63–68.

Sanders D, Johnson S, Kelso B. 2010. Invasive Aquatic Weeds in Louisiana. http://text.lsuagcenter.com/en/communications/publications/agmag/Archive/2010/fall/Invasive-Aquatic-Weeds-in-Louisiana.htm. Accessed April 16, 2013.

Schmitz DC, Schardt JD, Leslie AJ, Dray FA, Osborne JA, Nelson BV. 1993. The ecological impact and management history of three invasive alien aquatic plant species in Florida. B. N. McKnight (*ed.*), Biological pollution. The control and impact of invasive exotic species. Indiana Academy of Science, Indianapolis, IN, 261 pp.

Senseman SA (*ed.*). 2007. Herbicide Handbook. 9th ed. Weed Science Society of America, Lawrence, KS. 458 pp.

SePRO Corporation. 2009. Galleon SC Aquatic Herbicide. http://www.sepro.com/documents/Galleon_Label.pdf. Accessed April 16, 2013.

University of Florida. 2011. Plant Management in Florida Waters: 2,4-D Considerations. http://plants.ifas.ufl.edu/manage/developing-management-plans/herbicide-considerations/24-d-considerations. Accessed April 16, 2013.

University of Florida. 2012a. Plant Management in Florida Waters: Details about the Aquatic Herbicides used in Florida. http://plants.ifas.ufl.edu/manage/control-methods/details-about-the-aquatic-herbicides-used-in-florida. Accessed August 5, 2013.

University of Florida. 2012b. Plant Management in Florida Waters: Maintenance Control Strategies. http://plants.ifas.ufl.edu/manage/developing-management-plans/maintenance-control-strategy. Accessed April 16, 2013.

Weldon LW, Blackburn RD. 1966. Waterlettuce—nature, problem and control. Weeds 14:5–9.

Wersal RM, Madsen JD. 2010. Combinations of penoxsulam and diquat as foliar applications for control of waterhyacinth and common salvinia: evidence of herbicide antagonism. J. Aquat. Plant Manag. 48:21–25.