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Greenhouse Response of Six Aquatic Invasive Weeds to Imazamox

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ABSTRACT

Research was conducted to evaluate the response of six aquatic invasive weeds to imazamox (2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid). Alligatorweed, creeping water primrose, giant salvinia, parrotfeather, waterhyacinth, and water lettuce were treated with 35 to 560 g ae/ha imazamox and comparison treatments of 2240 g ae/ha glyphosate (N-(phosphonomethyl)glycine) and 560 g ae/ha imazapyr (2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1-*H*-imidazol-2-yl]-3-pyridinecarboxylic acid). Based on calculated EC_{70} values for dry weight reductions, weed species ranked by increasing imazamox sensitivity were giant salvinia (not calculable), water lettuce (533 g/ha), waterhyacinth (372 g/ha), parrotfeather (115 g/ha), creeping water primrose (116 g/ha), and alligatorweed (65 g/ha). Dry weights among all species were similar after treatment with 560 g/ha imazamox or imazapyr and were at least 79%, except for giant salvinia. Control of giant salvinia did not exceed 39% with imazamox or imazapyr but was 89% with glyphosate. Dry weight response of the other five species was equivalent between imazamox and glyphosate. Based on these results, five important invasive aquatic weeds were sensitive to imazamox, and future research should quantify the sensitivity under field conditions.

Key words: *Alternanthera philoxeroides,* aquatic plants, chemical control, *Eichhornia crassipes,* herbicides, *Ludwigia grandiflora, Myriophyllum aquaticum, Pistia stratiotes, Salvinia molesta.*

INTRODUCTION

Imazamox is a widely used herbicide in the imidazolinone herbicide family and inhibits the acetolactate synthase (also known as acetohydroxyacid synthase) enzyme (EC 4.1.3.18), which is critical for the synthesis of the amino acids valine, leucine, and isoleucine in plants (Tan et al. 2005). The chemical is absorbed through foliage and translocated through both xylem and phloem (Senseman 2007). Imazamox differs from other imidazolinones in

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that it contains a methoxymethyl functional group on its pyridine ring (Tan et al. 2005). Imidazolinones injure or kill a plant's apical meristem, releasing lateral meristems from apical dominance. In field crops, imazamox use rates range up to 45 g ae/ha and is effective against a large variety of grasses and broadleaf weeds, including downy brome (*Bromus tectorum* L.), red rice (*Oryza sativa* L.), shattercane (*Sorghum bicolor* [L.] Moench ssp. *arundinaceum* [Desv.] de Wet & Harlan), jointed goatgrass (*Aegilops cylindrica* Host), wild mustards, common ragweed (*Ambrosia artemisiifolia* L.), common lambsquarters (*Chenopodium album* L.), and others (Nelson and Renner 1998, Tan et al. 2005, BASF 2009). On aquatic sites, the foliar application rate is up to 560 g/ha. Imazamox is essentially nontoxic to birds, fish, and aquatic invertebrates and is slightly toxic to algae (EPA 1997, NRA 2000, BASF 2008). Little information has been reported on the efficacy of imazamox against aquatic weeds.

Invasive weeds can have numerous negative impacts on water bodies in the southeastern United States. Effects include blockage of drainage canals and water intakes, displacement of native species, increased breeding habitat for mosquitoes, reductions in dissolved oxygen levels, lowered property values, and other impacts (Orr and Resh 19989 McComas 2002, TVA 2002, AERF 2009). A few of the important emergent and floating species for this region include alligatorweed (*Alternanthera philoxeroides* [Mart.] Griseb.), creeping water primrose (*Ludwigia grandiflora* [Michx.] Greuter & Burdet), giant salvinia (*Salvinia molesta* L.), parrotfeather (*Myriophyllum aquaticum* [Vell.] Verdc.), waterhyacinth (*Eichhornia crassipes* [Mart.] Solms), and water lettuce (*Pistia stratiotes* L.).

Alligatorweed is a perennial herbaceous plant in the Amaranthaceae family that is able to grow in a range of conditions, from dry terrestrial to aquatic habitats; it may be rooted or free-floating and can survive completely immersed for several days. Alligatorweed can tolerate low light and brackish water conditions (Longstreth et al. 1984) and thrives in eutrophic waters (Julien et al. 1995). Native to South America, alligatorweed now has a nearly worldwide distribution in temperate and subtropical regions (Julien et al. 1995). In the United States, it was likely introduced from ballast water in the 1800s, and was first collected in 1897 near Mobile, Alabama (Kaufman and Kaufman 2007). It is found from Illinois south to Florida and west to Texas, and also in California. Alligatorweed is a federal noxious weed and a state-prohibited or noxious weed in Alabama, Arizona, Arkansas, California, Florida, South Carolina, and Texas (USDA NRCS 2009).

Creeping water primrose is a semi-aquatic freshwater perennial in the Onagraceae family. It grows in mud or forms floating mats up to 3 ft thick in eutrophic, slow moving water (Kaufman and Kaufman 2007). Native to South America, creeping water primrose was probably introduced to the United States as an ornamental. Specimens collected in the United States date from the early 1900s (Kaufman and Kaufman 2007). Its current distribution ranges from New York to Florida and west to Texas, plus Washington, Oregon, and California. *Ludwigia grandiflora* ssp. *grandiflora* is listed as a plant pest in South Carolina, while ssp. *hexapetala* is a weed in North and South Carolina and a quarantine weed in Washington (USDA NRCS 2009).

Giant salvinia is a free-floating aquatic pteridophyte in the Salviniaceae family. Plants have a pair of leaves and a third, highly dissected, modified leaf that functions as a root (Owens et al. 2004). Kaufman and Kaufman (2007) found that it can vegetatively double its biomass every 2 to 10 days. Buds and leaves deep in the leaf mats may be protected from frosts that kill exposed tissues. Giant salvinia inhabits slow-moving or still water and grows both in sun and shade (Kaufman and Kaufman 2007). Native to southeastern Brazil, the species is now found nearly worldwide (Groves et al. 1995). In the United States, this federal noxious weed has been documented in Hawaii and in 10 southern states from North Carolina to California (USDA NRCS 2009).

Parrotfeather is a freshwater, herbaceous perennial plant in the Haloragaceae family. It forms dense stands in still or slow-moving water (Weakley 2009) and provides excellent mosquito larvae habitat (Orr and Resh 1989). Hussner et al. (2009) found that parrotfeather is able to grow more than 1cm/d in drained soil, and that root density and growth rate have been shown to increase with available nutrients. Parrotfeather is native to South America and now has a nearly worldwide distribution (USDA ARS 2009), likely due to its popularity in the aquatic gardening and aquarium trades. In the United States, parrotfeather is distributed throughout the southeast, most of the lower Midwest, and several western states. It is a listed noxious weed in several states (USDA NRCS 2009).

Water lettuce is a free-floating perennial aquatic monocot in the Araceae family. Water lettuce prefers lakes and slow-moving streams, and its range is limited to regions with temperatures above 15 C (Rivers 2002). It is disputed as to whether or not the plant is native to the United States. John and William Bartram described it on Florida's St. Johns River in 1765, but it may have been introduced in ballast water from South American or African ships (Kaufman and Kaufman 2007). It has a worldwide distribution and is widely disseminated in the United States. Water lettuce is a listed noxious weed in Alabama, California, and Texas, and is prohibited in Connecticut and Florida (USDA NRCS 2009).

Waterhyacinth is a floating aquatic monocot in the Pontederiaceae family. It reproduces rapidly, producing dense mats under which dissolved oxygen content is significantly reduced (Rai and Munshi 1979). Native to Brazil, waterhyacinth can be found in many freshwater areas of the tropics and subtropics worldwide, as well as in the southeastern United States in ditches, ponds, rivers, and canals. Waterhyacinth is listed as a noxious weed in Alabama, Arizona, California, and Texas (USDA NRCS 2009). This species has very showy, large flowers that likely promote its spread as an ornamental plant where not regulated.

Due to the rapid growth and ability of these plants to invade, colonize, and take over a wide range of habitats, additional information is needed on plant response to herbicides, especially newly labeled aquatic herbicides like imazamox. Therefore, controlled greenhouse studies were conducted to evaluate the response of these selected weed species to imazamox, imazapyr, and glyphosate.

MATERIALS AND METHODS

Study One

Alligatorweed, creeping water primrose, and parrotfeather were collected from North Carolina infestations, keyed to species, and propagated. Shoot tips (approximately 5 to 10 cm in length) from propagated material were transplanted into 9 cm square pots containing a commercial potting mix[2]. Pots were kept saturated by irrigation three times daily and were fertilized weekly with water soluble fertilizer[3]. Plants were grown for about 3 weeks to establish root systems and shoot length of approximately 15 to 20 cm in height prior to treatment. Treatments included imazamox[4] at 35, 70, 140, 210, 280, and 560 g/ha, glyphosate[5] at 2240 g ae/ha, imazapyr[6] at 560 g ae/ha, and a nontreated control. Foliar treatments were applied with a single Teejet® XR8003 flat fan nozzle[7] at 280 L/ha spray volume using a pressurized CO_2 system. Herbicide solutions were mixed immediately prior to application and a nonionic surfactant[8] at 0.25% v/v was included.

Study Two

Giant salvinia, waterhyacinth, and water lettuce were collected from North Carolina infestations, keyed to species, and cultured in greenhouse mesocosms. Plants of uniform size were placed in 3.75 L buckets containing pond water and allowed to acclimate for 3 d. On the day of treatment, giant salvinia coverage was approximately 90% of the bucket and diameters of waterhyacinth and water lettuce were approximately 12 and 9 cm, respectively. Plants were transferred to 91 by 60 cm flats containing 7.5 cm tap water for treatment to prevent overspray leaving herbicide residue in or on the buckets. Herbicide rates, nonionic surfactant, and application methods were equivalent to those described for study one. After treatment, plant foliage was allowed to dry for approximately 1 h prior to placement back in buckets to eliminate any potential water residue. Water level in buckets was maintained (3.75 L) uniformly throughout the course of the trial by supplementing pond water as needed.

Each study was repeated in time and included four repetitions per treatment. In both studies, visual estimates of weed control were determined at 5 weeks after treatment (WAT) on a 0 to 100% scale, where 0% equals no plant response and 100% equals complete plant death. At 5 WAT, plant shoots (alligatorweed, creeping water primrose, and parrotfeather) or whole plants (giant salvinia, waterhyacinth, and water lettuce) were harvested and oven dried at 50 C for 72 h for biomass determination. Alligatorweed, creeping water primrose, and parrotfeather shoots were harvested again at 10 WAT to measure plant regrowth dry weight.

Data were subjected to analysis of variance (ANOVA), and means were separated using Fisher's Protected LSD ($P \leq 0.05$; SAS v. 9.1[9]). The nontreated control was not included in statistical analyses of visual ratings but was included in dry weight analyses. For ANOVA, all data were combined over trial runs because a treatment by trial repetition interaction was not observed. Plant dry weight data were converted to a percent of the nontreated control to improve homogeneity. Dry weight and visual control data for imazamox treatment means in each trial repetition were subjected to regression analysis using the logistic equation $y = a/1 + (x/x_o)^b$ (SigmaPlot 9.01[10]). Regression models were then used to calculate effective concentrations, which reduced dry weight to 70% of nontreated control dry weight values (EC_{70}). An EC_{70} value was selected because each regression curve crossed this arbitrary line, but none crossed 80%.

RESULTS AND DISCUSSION

Study One

Alligatorweed demonstrated a more rapid response to increasing imazamox rate than creeping water primrose or parrotfeather (Figure 1). Dry weight was 35% of the nontreated reference plants with 35 g/ha, and <20% of the nontreated reference with rates of 210 g/ha and greater. Calculated EC_{70} for alligatorweed dry weight was 55 g/ha. Alligatorweed regrowth dry weight also decreased rapidly with increasing imazamox rate, and the EC_{70} value was 65 g/ha. Regrowth dry weight was 24% of the nontreated reference with a rate of 70 g/ha, and <1% of the nontreated reference with rates of 210 g/ha and greater. Compared to 2240 g/ha glyphosate and 560 g/ha imazapyr, alligatorweed response to 560 g/ha imazamox was very similar (Table 1). Imazamox provided 94% visual control of alligatorweed, while control with glyphosate and imazapyr was 99 to 100%. Dry weights did not differ among the three treatments, and all were significantly lower than the nontreated reference.

Many annual Amaranthaceae species are controlled by imidazolinone chemistry, including imazamox. Prostrate (*Amaranthus albus* L.), redroot (*A. retroflexus* L.), and smooth (*A. hybridus* L.) pigweed, as well as Palmer (*A. palmeri* S. Watson) and spiny (*A. spinosus* L.) amaranth are controlled with imazamox at field crop use rates (BASF 2009). Sweat et al. (1998) reported that Palmer amaranth, redroot pigweed, tumble pigweed (*A. albus* L.), and one of two biotypes of common waterhemp (*A. rudis* Sauer) were controlled by imazamox, imazapyr, imazaquin (2-[4,5-dihydro-4-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-3-quinolinecarboxylic acid), and imazethapyr (2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid). Imazapyr is also registered for the control of *Amaranthus*, without any specification of species (BASF 2006). Sensitivity of *Amaranthus* species may indicate a broad sensitivity across

[2]Metro Mix® 200; Sun Gro Horticulture, Bellevue, WA.
[3]Miracle-Gro® Water Soluble Lawn Food 36-6-6; The Scotts Company, Marysville, OH.
[4]Clearcast®; BASF Corporation, Research Triangle Park, NC.
[5]Touchdown® Pro; Syngenta Crop Protection Inc., Greensboro, NC.
[6]Habitat®; BASF Corporation, Research Triangle Park, NC.
[7]Spraying Systems Company, Wheaton, IL.
[8]NIS; Induce®; Helena Chemical Co., Collierville, TN.

[9]SAS Institute Inc., Cary, NC.
[10]Systat Software, Inc., Point Richmond, CA. Received for publication March 2, 2010 and in revised form June 30, 2010.

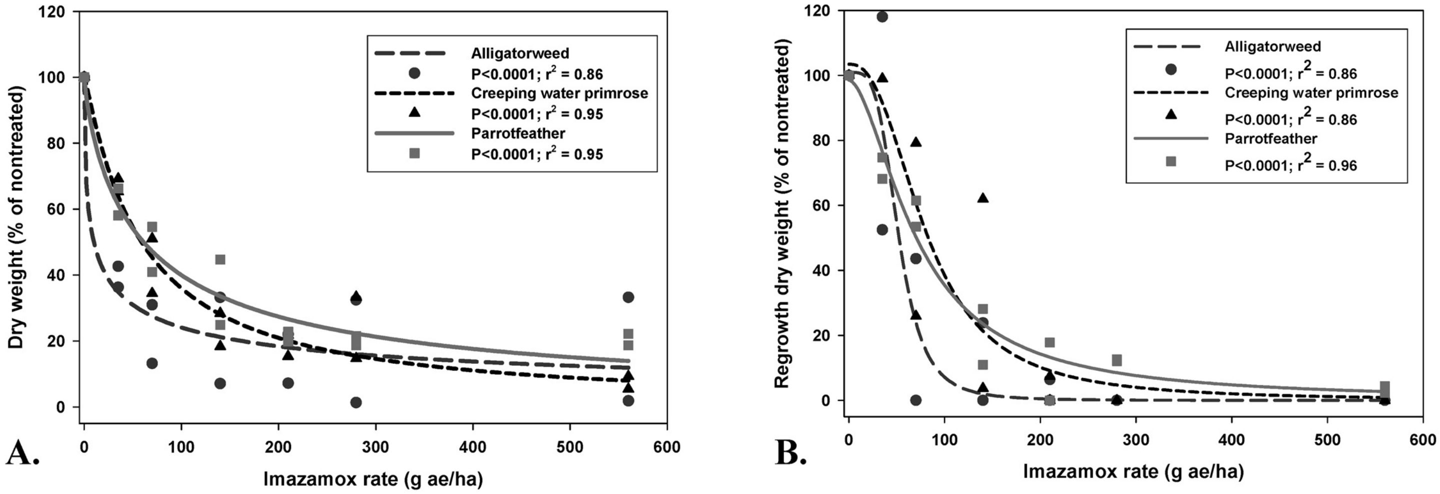

Figure 1. Response of alligatorweed, creeping water primrose, and parrotfeather dry weights (A) and regrowth dry weights (B) to imazamox. All curves were calculated using the logistic equation $y = a/(1 + (x/x_o)^b)$. Calculated EC_{70} values for alligatorweed, creeping water primrose, and parrotfeather dry weights were 55, 129, and 171 g/ha, respectively. Calculated EC_{70} values for alligatorweed, creeping water primrose, and parrotfeather regrowth dry weights were 65, 116, and 115 g/ha, respectively.

Amaranthaceae to imidazolinones, although this should be evaluated by additional research.

Creeping water primrose dry weight decreased with increasing imazamox rate (Figure 1). Dry weight was 64% of the nontreated reference plants with 35 g/ha, and 20% of the nontreated reference with 210 g/ha. The EC_{70} value for creeping water primrose dry weight was 129 g/ha, indicating slightly more tolerance than alligatorweed under these research conditions. Regrowth dry weight was 21% of the nontreated reference with 140 g/ha and <10% of the nontreated reference with rates of 210 g/ha and greater. The regrowth EC_{70} value was 115 g/ha. Imazamox provided 80% visual control of creeping water primrose at 560 g/ha, but better visual control was achieved with glyphosate and imazapyr at 92 to 93% (Table 1). However, there were no differences in weights among the three treatments, and each treatment resulted in lower weights than the nontreated control.

Parrotfeather response to imazamox was generally similar to that of creeping water primrose. Dry weight was approximately 60% of the nontreated reference with 35 g/ha, but declined to nearly 25 and 15% of control dry weights with 210 and 560 g/ha (Figure 1). The calculated EC_{70} for parrotfeather dry weight was 171 g/ha. Similar results were seen with parrotfeather regrowth after initial harvest. Dry weight was reduced from >60% of control dry weight with 35 g/ha to <10% of the control with 210 and 560 g/ha. The EC_{70} value for regrowth was 116 g/ha and very close to the 115 g/ha EC_{70} obtained on creeping water primrose. Visual parrotfeather control was slightly lower with 560 g/ha imazamox than with glyphosate or imazapyr, even though growth and regrowth dry weights were similar (Table 1). Imazamox achieved 81% control, compared to 93 and 94% with glyphosate and imazapyr. Dry weights did not differ significantly with the three treatments, averaging 0.62 g compared to the untreated dry weight of 3.15 g. Likewise, regrowth dry weight averaged 0.08 g from the treatments, compared to the untreated at 3.33 g.

In outdoor mesocosm research, Wersal and Madsen (2007) reported complete control of parrotfeather with 584 g/ha imazapyr, but only 53% control with 584 g/ha imazamox. A primary difference in these trials is that Wersal and Madsen (2007) used 3.78 L pots placed in 378 L tanks. Thus, some parrotfeather biomass would have been submersed and foliar coverage would not have been as great as in our trial, which had no submersed growth and nearly 100% foliar coverage. This distinction may have practical implications, and applicators may need to consider that as the proportion of submersed parrotfeather foliage increases, control from foliar-applied imazamox may decrease. This could certainly apply to other herbicides as well, and additional research should be conducted to verify or refute this hypothesis. Mohr et al. (2007) found that glyphosate interception and absorption by velvetleaf was impacted by the diurnal movement of the leaves, resulting in significantly lower control when less leaf biomass was in contact with the herbicide.

Study Two

Giant salvinia was not controlled by imazamox, therefore the regression analysis is not reported. Visual control with 560 g/ha imazamox was only 18% and lower than imazapyr at 39% (Table 2). Giant salvinia dry weight was similar after imazapyr and imazamox treatment at 10.3 to 12.18 g. These values were lower than the nontreated reference at 18.38 g, representing a reduction of 34 to 44%. Glyphosate provided 89% visual control and reduced dry weight to 18% of the nontreated reference. The discrepancy between visual signs of control and dry weight of giant salvinia after imazamox treatment is likely due to some growth regulation provided by the herbicide. Salvinia coverage in the buckets after imazamox treatment was 100%, but the floating mat was less dense than the control; thus, there was less biomass than appeared visually. Imazamox is being evaluated as a growth reg-

Table 1. Control and dry weights of alligatorweed, creeping water primrose, and parrotfeather after foliar applications of glyphosate, imazamox, and imazapyr.[A,B]

		Alligatorweed			Creeping water primrose			Parrotfeather		
Herbicide[c]	Rate	Control[d]	Dry wt.	Regrowth Dry wt.	Control	Dry wt.	Regrowth Dry wt.	Control	Dry wt.	Regrowth Dry wt.
	g ae/ha	%	---------- g% ----------		%	---------- g% ----------		%	---------- g% ----------	
Glyphosate	2240	100 a	0.31 b	0 b	92 a	0.87 b	0.07 b	94 a	0.49 b	0.03 b
Imazamox	560	94 b	1.12 b	0.12 b	80 b	1.02 b	0 b	81 b	0.97 b	0.20 b
Imazapyr	560	99 a	0.83 b	0 b	93 a	1.03 b	0 b	93 a	0.39 b	0 b
Nontreated control	—	—	6.40 a	3.40 a	—	4.97 a	4.13 a	—	3.15 a	3.33 a

[a]Weed control rated visually at 5 weeks after treatment (WAT) on 0 to 100% scale; 0% = no plant response and 100% = complete death. Plants harvested for dry weight determination at 5 WAT and harvested for regrowth dry weight determination at 10 WAT.
[b]Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD ($P \leq 0.05$).
[c]Non-ionic surfactant at 0.25% included with all herbicide applications.

Table 2. Control and dry weights of giant salvinia, waterhyacinth, and water lettuce five weeks after foliar applications of glyphosate, imazamox, and imazapyr.[A,B]

		Giant salvinia		Waterhyacinth		Water lettuce	
Herbicide[c]	Rate	Control	Dry weight	Control	Dry weight	Control	Dry weight
	g ae/ha	%	g	%	g	%	g
Glyphosate	2240	89 a	3.39 c	99 a	0.53 c	100 a	0.09 c
Imazamox	560	18 c	12.18 b	94 a	1.14 bc	89 a	0.58 bc
Imazapyr	560	39 b	10.3 b	79 b	1.78 b	98 a	2.20 b
Nontreated control	—	—	18.38 a	—	2.93 a	—	4.65 a

[a]Weed control rated visually at 5 weeks after treatment (WAT) on 0 to 100% scale; 0% = no plant response and 100% = complete death. Plants harvested for dry weight determination at 5 WAT and harvested for regrowth dry weight determination at 10 WAT.
[b]Means within a column followed by the same letter are not significantly different according to Fisher's Protected LSD ($P \leq 0.05$).
[c]Non-ionic surfactant at 0.25% included with all herbicide applications.

ulator for dioecious *Hydrilla verticillata* (L.f.) Royale (Burns 2008), likely with the belief that regulated growth may maintain fish habitat while reducing the negative impacts resulting from prolific growth. Due to biological differences between floating and submersed weeds and the resulting ecological effects, growth regulator activity would provide little benefit for floating weed management programs when used without other management techniques.

Waterhyacinth dry weight was reduced to 48% of the nontreated reference with 210 g/ha, and to 20% of the nontreated reference with 560 g/ha, based on the regression model (Figure 2). The calculated EC_{70} value was 372 g/ha. Imazamox and glyphosate provided equivalent control of waterhyacinth at 94 to 99%, while control with imazapyr was lower at 79% (Table 2). Waterhyacinth dry weight was lower with the treatments than the nontreated reference at 2.93 g. Dry weight with imazamox treatment was 1.14 g, which did not differ from that of glyphosate (0.53 g) or imazapyr (1.78 g), although the latter two did differ. Waterhyacinth has been reported to be controlled by 500 g/ha imazapyr (Kannan and Kathiresan 2002) and imazamox (Burns 2008), although application rate and other details were not reported for imazamox research. Our research supports the previous study, but also suggests that higher use rates will likely be required in the field for acceptable control.

All herbicides provided visual control of water lettuce at 89 to 98% (Table 2). Water lettuce dry weight was 47% of the nontreated reference with 210 g/ha and reduced to 29% of the nontreated reference with 560 g/ha (Figure 2). Dry weight of the nontreated reference was 4.65 g and was greater than the three herbicide treatments. Glyphosate treatment resulted in the lowest dry weight at 0.09 g, while imazapyr resulted in dry weight of 2.20g. Dry weight of water lettuce treated with imazamox did not differ from either glyphosate or imazapyr.

In this research, imazamox controlled alligatorweed, creeping water primrose, parrotfeather, waterhyacinth, and water lettuce. The floating species evaluated were more tolerant of imazamox than the emergent species. Giant salvinia was not controlled at any rate, while 372 to 533 g/ha were required for 70% control of waterhyacinth and water lettuce. In contrast, rates of 171 g/ha or lower reduced dry weight of the three emergent species by at least 70%. Dry weight response of the six species was generally similar among 2240 g/ha glyphosate, 560 g/ha imazapyr, and 560 g/ha imazamox, with the notable exception of giant salvinia controlled by glyphosate, but not imazamox or imazapyr. These data provide a baseline for field expectations, although additional research is needed to verify under field conditions. Submersed shoot biomass, plant growth stage, time of year, and environmental conditions may influence field efficacy.

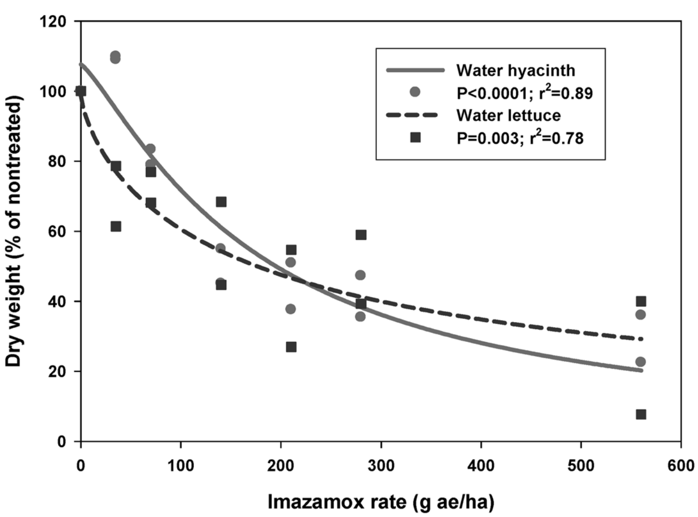

Figure 2. Response of waterhyacinth and water lettuce dry weights to imazamox. Both curves were calculated using the logistic equation $y = a/(1 + (x/x_o)^b)$. Calculated EC_{70} values for waterhyacinth and water lettuce dry weights were 372 and 533 g/ha, respectively.

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