New herbicides and tank mixes for control of waterhyacinth in the Sacramento–San Joaquin Delta

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ABSTRACT

The Sacramento–San Joaquin Delta is the largest freshwater estuary on the West Coast of the United States. Delta habitat and economic utility are compromised by waterhyacinth, a floating aquatic weed. Standard control measures for waterhyacinth include foliar treatment with glyphosate or 2,4-D. We have conducted trials over three seasons to evaluate efficacy of newly registered, low–use-rate aquatic herbicides. In 2017, we evaluated waterhyacinth control using carfentrazone (133 g ai ha^{-1}), flumioxazin (322 g ai ha^{-1}), imazamox (280 g ae ha^{-1}), and florpyrauxifen-benzyl (29.4 and 58.8 g ai ha^{-1}), as well as various tank mixes, compared with a standard rate of glyphosate (1,681 g ae ha^{-1}). Plots were established in floating 1-m^2 quadrats, and treatments were replicated four times. All treatments were applied in 935 L ha^{-1} solution with 3.5 L ha^{-1} nonionic surfactant. We also included treatments with glyphosate (1,681 g ae ha^{-1}) in lower spray volumes of 234 and 468 L ha^{-1}. We collected biomass samples at 8 wk after treatment (WAT). Three treatments reduced waterhyacinth biomass by $>$ 95%: florpyrauxifen-benzyl (58.8 g ai ha^{-1}), flumioxazin + imazamox (322 + 280 g ai/ae ha^{-1}), and the 468 L ha^{-1} application of glyphosate (1,681 g ae ha^{-1}). Tank mixes (flumioxazin + imazamox, carfentrazone + imazamox, carfentrazone + glyphosate, and flumioxazin + glyphosate) gave approximately additive control. Florpyrauxifen-benzyl and flumioxazin + imazamox may be effective alternatives to glyphosate for controlling waterhyacinth with reduced rates of active ingredient. Glyphosate applied in a spray volume of 468 L ha^{-1} produced better control than the same rate of glyphosate in 935 L ha^{-1}, suggesting that spray-volume optimization may be a useful topic for future research.

Key words: carfentrazone, carrier volume, *Eichhornia crassipes* (Mart.) Solms, florpyrauxifen-benzyl, flumioxazin, glyphosate, tank mixtures.

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INTRODUCTION

The Sacramento–San Joaquin Delta (hereafter Delta) is the largest freshwater estuary on the West Coast of the United States, comprising 3,370 km^2 (1,300 mi^2) of marshland, small lakes (locally referred to as *islands*), canals and waterways, and diked farmland at the confluence of the Sacramento and San Joaquin rivers (DSC 2013). The Delta comprises a critical environmental and economic resource. It is a critical habitat for fish and wildlife, both resident and migratory (e.g., Moyle et al. 2016; Shuford et al. 2019). It also serves as the nexus of water transport in California, with water pumped from the southern end into the California Aqueduct, where it is used as a domestic water source for 27 million people and irrigates 1.2 million ha (3 million ac; DSC 2013).

Delta habitat and economic utility are compromised by invasive species, including waterhyacinth [*Eichhornia crassipes* (Mart.) Solms], a floating aquatic weed ranked by some authors as one of the world's worst invasive species (Holm et al. 1977, Lowe et al. 2000). Past control measures for waterhyacinth include foliar treatment with glyphosate or 2,4-D, both of which are subject to increasing public and regulatory concern (CDBW 2017). To address that, we have conducted trials over three seasons to evaluate the efficacy of newly registered aquatic herbicides that are applied at much lower rates of active ingredient than glyphosate or 2,4-D.

Waterhyacinth was first observed in California in 1904 (Bock 1968) but was not specifically noted in the Delta until the 1970s (Stewart et al. 1988). The State of California has been actively managing waterhyacinth in the Delta since 1983 (Stewart et al. 1988).

Only a small fraction of known herbicides are labeled for use in aquatic environments by the U.S. Environmental Protection Agency (USEPA), and a smaller subset is appropriate for management of waterhyacinth (Netherland 2014). In previous trials (2015 to 2016), it was found that imazamox (280 to 560 g ae ha^{-1}) and penoxsulam (25 to 98 g ai ha^{-1}) provided better control of waterhyacinth compared with standard rates of glyphosate (1,681 g ae ha^{-1}) or 2,4-D (1,065 g ae ha^{-1}; Madsen and Kyser, 2020). This suggests that availability of these newly registered chemicals may allow control of waterhyacinth with reduced rates of active ingredient, as well as providing alternative modes of action to help manage the potential for herbicide resistance.

Carfentrazone-ethyl is a broadleaf contact herbicide used primarily in grain crops, such as wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), corn (*Zea mays* L.), and others, to supplement other herbicides (Shaner 2014). It was labeled for aquatic use by the USEPA in 2004 and has been used successfully on waterlettuce (*Pistia stratiotes* L.) and duckweed (*Lemna* L. spp.) and in tank mixes with systemic herbicides for emergent aquatic plants (Netherland 2014).

Flumioxazin is a contact herbicide used for preemergent control of some terrestrial weeds, as well as burndown of weeds in reduced-tillage programs in row crops (Shaner 2014). It has also been used in orchard, forestry, and natural area weed management (Richardson and Zandstra 2009, Rankova and Popov 2011, MacDonald et al. 2013). Flumioxazin was labeled for aquatic use in 2011 and has been used successfully for control of waterlettuce, duckweed, and watermeal (*Wolffia* Horkel ex Schleid. spp., Netherland 2014). It works in both submersed and emergent weed control.

Florpyrauxifen-benzyl is an arylpicolinate herbicide with auxin-like activity that has been developed for rice production and aquatic weed management (Netherland and Richardson 2016, Miller and Norsworthy 2018). Florpyrauxifen-benzyl is effective on a number of emergent, floating, and submersed aquatic plants, including some monocots, at relatively low rates (Netherland and Richardson 2016, Richardson et al. 2016).

Glyphosate is a broad-spectrum, foliar-applied, systemic herbicide (Shaner 2014). Glyphosate is used in both crop and noncrop applications and is the most-used herbicide in the world (Woodburn 2000, Duke and Powles 2008). Glyphosate was labeled for aquatic use in 1977 to control floating and emergent plants (Netherland 2014).

Imazamox is an imidazolinone herbicide that acts as an acetolactate synthase (ALS) inhibitor (Shaner 2014). It is widely used in row crops that are tolerant to imidazolinone, such as Clearfield© rice and wheat (Shaner 2014). The USEPA approved an aquatic-use label for imazamox in 2008, where it has been used on weeds, such as common reed [*Phragmites australis* (Cav.) Trin. ex Steud.], Chinese tallowtree [*Triadica sebifera* (L.) Small, upland and riparian), and waterhyacinth (Netherland 2014). Imazamox has had somewhat limited use against submersed plants but is effective for suppression of hydrilla [*Hydrilla verticillata* (L. f.) Royle] and curlyleaf pondweed (*Potamogeton crispus* L.; Netherland 2014).

Using mixtures of two or more herbicides ("tank mixes") has been a common practice among applicators for decades but has received somewhat less attention in research than work with individual herbicides. With the development of weed populations resistant to glyphosate and other herbicides, the use of herbicide mixes has been recommended as one of many steps to reduce the selection and spread of resistant plant populations (Diggle et al. 2003). Use of herbicide mixtures may also broaden the spectrum of plants controlled, increase the level of control for a given weed, and allow the use of lower herbicide rates (Ross and Lembi 2009). Herbicides in a mixture may exhibit one of three possible interactions: synergism, additivity, or antagonism. The most common interaction is additivity, in which the response is equivalent to the sum of the predicted effects of each herbicide alone. Synergism is when the herbicide mixture exhibits greater activity than would be predicted by the sum of the effects of individual herbicides. In antagonism, the activity of the mixture is less than that predicted from the sum of the effects of individual herbicides (Ross and Lembi 2009). We included tank mixtures in this study to compare their efficacy versus individual herbicides.

In the current study, we evaluated waterhyacinth control using recently registered aquatic-use formulations of carfentrazone[1] (133 g ai ha^{-1}), flumioxazin[2] (322 g ai ha^{-1}), imazamox[3] (280 g ae ha^{-1}), and florpyrauxifen-benzyl[4] (29.4 and 58.8 g ai ha^{-1}), as well as various tank mixes of either carfentrazone or flumioxazin with either glyphosate or imazamox, compared with a standard rate of glyphosate[5] (1,681 g ae ha^{-1}).

MATERIALS AND METHODS

We conducted this study on a sheltered water body (38°0′3″N, 121°34′18″W) at the approximate center of the Sacramento–San Joaquin Delta. Local depths ranged from ~1 m at low tide to 2 m at high tide. Although this site is 85 km from the mouth of the San Francisco Bay and the water is fresh, it undergoes about 1 m of daily tidal fluctuation. Water temperature ranged from 17 to 30 C (63 to 86 F) during the course of the trials, and air temperature ranged from 11 to 35 C.

Plots were established in floating 1-m^2 quadrats made of 6-cm-diameter polyvinyl chloride (PVC) tubing anchored with cinderblocks. Quadrats were "planted" with rosettes of waterhyacinth collected nearby, filling each quadrat to approximately 50% cover. We waited 2 wk before treating to allow waterhyacinth to grow and fill each quadrat.

We treated plots 13 June 2017, using a CO_2 backpack sprayer carried on the deck of a flat-bottom boat and running a 1.5-m boom with three TeeJet® AIXR11004 nozzles[6] at 207 kPa. Wind was calm at application, and air temperature was 27 C. Treatments were replicated four times in randomized complete blocks. All treatments were made as foliar applications, broadcast over the plants in 935 L ha^{-1} spray solution with a 3.5 L ha^{-1} crop oil concentrate surfactant.[7] In addition to the new chemicals and tank mixes (Table 1), we included treatments with glyphosate (1,681 g ae ha^{-1}) in reduced spray volumes of 234 and 468 L ha^{-1} to evaluate whether spray volume had any influence on efficacy (Table 2).

To evaluate treatment effects, we took subsamples from each plot 8 wk after treatment (WAT; whole plants from two 0.1-m^2 quadrats per plot). Samples were dried at 70 C for at least 48 h, then weighed (Madsen 1993, Madsen and Wersal 2017). Biomass was compared among individual and tank-mix treatments using ANOVA, followed by means separation using the Student's t test ($\alpha = 0.05$). A second ANOVA and means separation was performed on the three glyphosate spray volume treatments. Potential herbicide interactions in tank mixes were evaluated using the Colby method (Colby 1967) followed by Wilcoxon/Kruskal-Wallis rank-sum comparisons (Wersal and Madsen 2010). The Colby method allows evaluation of herbicide interactions in a relatively simple trial, as compared with isobolic analysis,

Table 1. Individual and tank mix treatments and waterhyacinth biomass yields. Colby analysis of tank mix results found no significant interactions.

Active Ingredient	Rate, g ha^{-1} (ai or ae)	Spray Volume , L ha^{-1}	Biomass Yield[a] , g DW m^{-2}	Control (%) Based on Biomass Reduction	Expected Control (%) in Colby Analysis
Untreated	—	—	1,479 a	—	—
Carfentrazone	133	935	1,032 b	30	—
Flumioxazin	322	935	1,041 ab	30	—
Glyphosate	1681	935	461 cd	69	—
Imazamox	280	935	203 cd	86	—
Florpyrauxifen-benzyl	29.4	935	400 cd	73	—
Florpyrauxifen-benzyl	58.8	935	19 d	99	—
Carfentrazone + imazamox	133 + 280	935	213 cd	86	90
Carfentrazone + glyphosate	133 + 1,681	935	466 cd	68	78
Flumioxazin + imazamox	322 + 280	935	74 d	95	90
Flumioxazin + glyphosate	322 + 1681	935	599 bc	59	78

Abbreviation: DW, dry weight.
[a]Biomass values followed by the same letter are not different at $\alpha = 0.05$ (Student's t test).

which requires multiple rates of each herbicide and mixture (Akobundu et al. 1975). The Colby treatment uses the following equation:

$$E = (X + Y) - \left(\frac{XY}{100}\right)$$

where E is the expected control with herbicides $A + B$, X is the observed control with herbicide A, and Y is the observed control with herbicide B.

RESULTS AND DISCUSSION

The contact herbicide flumioxazin (322 g ai ha^{-1}) did not significantly reduce biomass relative to the untreated reference (Table 1). This result may have been influenced by regrowth after treatment because the harvest was 8 WAT. The contact herbicide carfentrazone (133 g ai ha^{-1}) performed only slightly better. Wersal and Madsen (2012) obtained 89% control of waterhyacinth with carfentrazone at a similar rate at 4 WAT. Koschnick et al. (2004) reported > 90% control for waterhyacinth treated with carfentrazone at a similar rate at 25 d after treatment (DAT). Mudge and Netherland (2014) reported no significant control of waterhyacinth with higher rates of flumioxazin than used in this study.

All systemic herbicide treatments resulted in at least some reduction in biomass compared with untreated control plots (Table 1). Glyphosate (1,681 g ae ha^{-1}) reduced biomass 69% at 8 WAT; by comparison, Lopez (1993) reported > 90% control of waterhyacinth with glyphosate at 2.4 kg ha^{-1}. Emerine et al. (2010) reported 99% control of waterhyacinth with glyphosate at 2.2 kg ae ha^{-1}, and Mudge and Netherland (2014) found > 80% control with glyphosate at the same rate. In the current study, imazamox (280 g ae ha^{-1}) reduced biomass 86%. Mudge and Netherland (2014) had > 90% control of waterhyacinth at a similar rate of imazamox, and Emerine et al. (2010) found 94% control of waterhyacinth with a higher rate of 540 g ae ha^{-1}.

Florpyrauxifen-benzyl demonstrated activity at the low rate (29.4 g ae ha^{-1}) by reducing biomass by 73%, and at the high rate (58.8 g ae ha^{-1}) reduced biomass by 99% (Table 1). These results are consistent with those observed for a foliar treatment on Uruguay waterprimrose [*Ludwigia hexapetala* (Hook. & Arn.) Zardini, Gu, & P. H. Raven] treated at 29.4 g ae ha^{-1}, which resulted in 99% control (Enloe and Lauer 2017). This herbicide is very active at low application rates on species that typically respond to auxin herbicides.

Tank mixtures of herbicides receive additional scrutiny at both federal and California state regulatory levels; a pervasive concern is that the herbicides will act synergistically to create greater toxic effects on nontarget organisms. However, the potential value of tank mixtures for increasing the spectrum of efficacy, reducing potential for herbicide resistance, and decreasing the lag time to effective control are worth pursuing further. In particular, the length of time to effective control and the persistence of dead plants in a mat are confounding issues in the matter of weed control. In these trials, tank mixes of carfentrazone + imazamox (133 + 280 g ae ha^{-1}) and flumioxazin + imazamox (322 + 280 g ai/ae ha^{-1}) provided 86 and 95% control, respectively (Table 1). Tank mixes of carfentrazone + glyphosate (133 + 1,681 g ae ha^{-1}) and flumioxazin + glyphosate (322 + 1,681 g ae ha^{-1}) yielded 68 and 59% control, respectively. Using the Colby method to calculate expected results for tank mixtures

Table 2. Glyphosate spray volume treatments and waterhyacinth biomass yields. Treatment effects were analyzed separately from individual and tank-mix treatments (see Table 1).

Active Ingredient	Rate, g ha^{-1} (ai or ae)	Spray Volume, L ha^{-1}	Biomass Yield[a], g DW m^{-2}	Control (%) Based on Biomass Reduction
Glyphosate	1,681	935	461 a	69
Glyphosate	1,681	438	31 b	98
Glyphosate	1,681	234	394 ab	73

Abbreviation: DW, dry weight.
[a]Biomass values followed by the same letter are not different at $\alpha = 0.05$ (Student's t test).

based on observed results for individual herbicides, we found only minor deviations from expected outcomes (Table 1). None of these were significant based on Wilcoxon/Kruskal-Wallis rank-sum comparisons, indicating that these herbicide mixes produced simply additive effects.

Glyphosate applied in a spray volume of 468 L ha^{-1} produced better control than the same rate of glyphosate in 935 L ha^{-1}, but the same rate in 234 L ha^{-1} produced intermediate results (Table 2). Although these results are inconclusive, the findings suggest that spray-volume optimization may be a useful topic for future research. Similar results were seen by Van et al. (1986) in treating waterhyacinth with glyphosate in a series of spray volumes. Other findings in the current trial suggest that florpyrauxifen-benzyl and flumioxazin + imazamox may be effective alternatives to glyphosate for controlling waterhyacinth with reduced rates of active ingredient. Their availability also will facilitate management for herbicide resistance.

SOURCES OF MATERIALS

[1]Stingray®, SePRO Corporation, 11550 N. Meridian St., Suite 600, Carmel, IN 46032.

[2]Clipper™, Valent U.S.A. Corporation, P.O. Box 8025, Walnut Creek, CA 94596-8025.

[3]Clearcast®, SePRO Corporation, 11550 N. Meridian St., Suite 600, Carmel, IN 46032.

[4]ProcellaCOR™ EC, SePRO Corporation, 11550 N. Meridian St., Suite 600, Carmel, IN 46032.

[5]Roundup Custom™, Monsanto Company, 800 N. Lindbergh Blvd., St. Louis, MO 63167.

[6]TeeJet Technologies Illinois, LLC, 1801 Business Park Drive, Springfield, IL 62703.

[7]Agri-dex®, Helena Chemical Company, 225 Schilling Blvd., Suite 300, Collierville, TN 38017.

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