J. Aquat. Plant Manage. 52: 85–89

NOTES

Comparison of late-season herbicide treatments for control of emergent flowering rush in mesocosms

RYAN M. WERSAL, A. G. POOVEY, J. D. MADSEN, K. D. GETSINGER, AND C. R. MUDGE*

INTRODUCTION

Flowering rush (*Butomus umbellatus* L.) is native to Eurasia and in North America can form dense monospecific stands, that interfere with water uses and displace native plants (Countryman 1970). It grows both as an emergent plant along shorelines and as a submersed plant in deeper water (1 to 3 m) of northern lakes and rivers. Chemical management of flowering rush is still in the formative stages of field development and implementation, because few studies have been completed in this area. Although both emergent and submersed forms create nuisances, each morphological type might require an independent control strategy.

Herbicides applied directly to the water column are used to manage submersed plants whereas foliar applications are used to manage emergent plants. Successful submersed applications must expose target plants to a sufficient aqueous herbicide dose, determined by product-specific herbicide concentration and exposure time (CET) relationships (Getsinger and Netherland 1997). In the field, CET relationships are driven by water exchange processes surrounding treated plants (Getsinger et al. 1996). In many northern sites where flowering rush grows, high water flows caused by snowmelts and spring rains greatly increase rates of water exchange. Sustained high flows reduce potential herbicide CET relationships to the point of precluding submersed applications until water levels stabilize later in the growing season. In other northern sites without high water flows during spring, such as Detroit Lakes, Minnesota, early-season submersed applications of herbicides can reduce flowering rush (Madsen et al. 2013). In contrast, foliar applications are not influenced by aqueous CET relationships, because products are applied directly to aerial shoot surfaces.

Contact aquatic herbicides controlled submersed flowering rush when adequate CET relationships were maintained in growth-chamber experiments (Poovey et al. 2012, Poovey et al. 2013). Submersed applications of diquat (6,7-dihydrodipyrido [1,2-α:2′,1′-*c*] pyrazinediium dibromide), endothall (dipotassium salt) (7-oxabicyclo [2.2.1] heptane-2,3-dicarboxylic acid), and flumioxazin (2-[7-fluoro-3,4-dihydro-3-oxo-4-(2-propynyl)-2*H*-1,4-benzoxazin-6-yl]-4,5,6,7-tetrahydro-1*H*-isoindole-1,3(2*H*)-dione) to young, submersed flowering rush plants reduced biomass under short exposure times in small-scale trials. Submersed applications of the systemic herbicides 2,4-D [(2,4-dichlorophenoxy)acetic acid] and triclopyr ([(3,5,6-trichloro-2-pyridinyl)oxy]acetic acid), were less effective than contact herbicides under similar conditions. Static exposures of fluridone (1-methyl-3-phenyl-5-[3-(trifluoromethyl)phenyl]-4(1*H*)-pyridinone), imazamox (2-[4,5-dihydro-4 methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid), and bispyribac-sodium (sodium 2,6-bis[(4,6-dimethoxy-2-pyrimidinyl)oxy]benzoic acid) also were not effective against submersed flowering rush (Poovey et al. 2013).

Foliar applications of systemic aquatic herbicides have also reduced biomass of emergent flowering rush. Foliar applications of imazamox (4.7 L ha^{-1} [2 qt ac^{-1}]) suppressed flowering rush for one growing season in a field demonstration in Flathead Lake, MT (Rice et al. 2009). Concomitant applications of triclopyr (18.8 L ha^{-1} [8 qt ac^{-1}]) initially injured flowering rush, although treated areas were similar to reference areas by the end of the growing season (Rice et al. 2009). These applications were done in late May during spring to decrease shoot production and reproduction. Because flowering rush plants in Flathead Lake are reportedly triploid (Lui et al. 2005), they reproduce primarily through rhizome lateral branching and rhizome buds (Hroudová and Zákravský 1993). For long-term control of triploid flowering rush, it is essential that aquatic herbicides either translocate to the plant's roots and rhizomes or interrupt photosynthesis by killing the plant's shoots, or both, which in turn reduces root and rhizome biomass by limiting resource allocation. A more thorough

*First author: Aquatic Plant Scientist, Lonza, 1200 Bluegrass Lakes Pkwy., Alpharetta, GA 30004. Second, fourth, and fifth authors: Research Biologists, US Army Engineer Research and Development Center, 3909 Halls Ferry Rd., Vicksburg, MS 39180. Third author: Associate Research and Extension Professor, Geosystems Research Institute, Box 9652, Mississippi State, MS 39762. First author's previous position and address: Post-Doctoral Associate, GeoSystems Research Institute, Box 9652, Mississippi State, MS 39762. Corresponding author's E-mail: ryan.wersal@lonza.com. Received for publication October 1, 2013 and in revised form April 23, 2014.

Table 1. Percent control of triploid flowering rush collected from Detroit Lake, Minnesota and grown in mesocosms in Starkville, MS following late season submersed and foliar applications of herbicides from 1 to 6 wk after treatment (WAT).

Treatment	Manufacturer[2]	Rate/Concentration	Percent control WAT					
			1	2	3	4	5	6
Submersed applications		*Aqueous concentration (mg L^{-1})*						
2,4-D	2	4	0	0	0	0	0	5
2,4-D + surfactant[3]		4	5	5	5	0	5	5
Triclopyr	3	1.25	0	0	5	5	0	0
2,4-D + Triclopyr		4 + 1.25	0	0	0	10	30	50
Imazamox	4	0.5	0	0	0	5	5	5
Foliar applications[4]		*Foliar application rate (g ha^{-1})*						
2,4-D		4,261.2	10	15	45	60	60	50
Triclopyr		3,364.1	50	80	90	90	90	90
2,4-D + Triclopyr		4,261.2 + 3,364.1	25	80	90	95	95	95
Aminopyralid	5	140.2	90	95	95	95	95	95
Imazamox		560.7	0	15	30	85	90	95
Imazapyr	6	1,682.1	0	20	55	80	95	95
Glyphosate	7	4,541.5	5	5	10	25	70	80
Imazamox + Glyphosate		560.7 + 4,541.5	0	15	45	65	90	95
Imazapyr + Glyphosate		1,682.1 + 4,541.5	0	50	90	95	95	100

[1]With the exception of amniopyralid, all products evaluated in this study have U.S. Environmental Protection Agency-approved Section 3 labels for use in aquatic sites. Aminopyralid is being considered for an aquatic label at time of this publication.
[2]Numbers refer to the Sources of Materials list.
[3]The same amount of surfactant was added to select submersed applications as foliar applications, 0.98 ml, to determine if increased efficacy could be achieved in submersed applications by using a penetrant.
[4]A surfactant (1% v/v) was added to all foliar treatments.

understanding of flowering rush phenology is needed to establish resource allocation patterns.

Using other species as a guide, identifying high or low carbohydrate storage partitioning in the plant is possible (Madsen 1997, Woolf and Madsen 2003, Wersal et al. 2011, Wersal et al. 2013). In triploid flowering rush, maximum shoot biomass occurred approximately 8 wk after propagation, and maximum root and rhizome biomass occurred 18 wk after propagation in a greenhouse experiment (Hroudová and Zákravský 1993). Similarly, flowering rush shoot biomass peaked 8 wk after sprouting, and root and rhizome biomass increased 10 to 12 wk after sprouting in four Minnesota lakes (Madsen et al. 2011). When maximum shoot biomass of flowering rush was achieved, root and rhizome biomass was at its lowest levels (Marko et al. 2012), which suggests that carbohydrate storage is also likely at a low point in the roots/rhizomes (Madsen 1997, Wersal et al. 2013).

Consequently, timing herbicide applications before resources are moved from emergent tissues to belowground tissues could maximize efficacy by translocating herbicide to root and rhizome tissue, or reduce resource allocation to roots and rhizomes by controlling shoot biomass. Therefore, the objective of the study was to compare efficacy between foliar and submersed late-season applications of phloem-mobile ALS inhibitors and auxin-mimicing herbicides against late-stage (flowering) emergent flowering rush.

MATERIALS AND METHODS

The experiment was conducted in an outdoor mesocosm facility at the R. R. Foil Plant Research Station, Mississippi State University, Starkville, Mississippi, for 15 wk beginning in July 2010 and ending in October 2010. To date, natural populations of flowering rush have not been observed growing in Mississippi; however, this species grows well under mesocosm conditions in Mississippi. Therefore, documented triploid flowering rush was used in this study and was cultured from rhizomes collected from Big Detroit Lake, Minnesota (Lui et al. 2005).

To facilitate sprouting, 8- to 10-cm rhizome segments were floated in pond water in outdoor tanks for 10 to 14 d. One sprouted rhizome segment was planted in a 3.8-L plastic pot that was filled with a mixture of topsoil, loam, and masonry sand, and amended with 2 g L^{-1} of 19–6–12 Osmocote® fertilizer.[1] Six pots were placed into each of 64, 378-L treatment tanks (135 cm length by 79 cm width by 64 cm depth), with plants from four tanks used for a pretreatment biomass estimate. Water level in all tanks was maintained at 40 cm (volume = 216 L). Flowering rush acclimated in the tanks for approximately 8 wk until emergent shoots were tall and dense, ensuring that mature plants were present for late growth-stage applications. Water temperatures in the tanks averaged 22.8 C and ranged from 10.5 to 32.7 C. Prior to treatment, emergent growth ranged from 30 to 70 cm above the water surface and flowering had initiated in 10% of the tanks. Flowering and seed production in triploid flowering rush is limited (Lui et al. 2005), although as in other aquatic plants, it is likely a signal that shoot growth has been maximized and serves as a trigger for initiation of biomass reallocation to submersed structures.

One day prior to treatment, pretreatment biomass was harvested and sorted to shoots or roots and rhizomes, with no differentiation between root and rhizome tissue. All tissues were dried at 70 C for 72 h to determine dry weight. Following the pretreatment growth period, herbicides were applied to the water column for a submersed application or to the shoot mass for a foliar application (Table 1). For submersed applications, a concentrated solution was ap-

plied to each tank to provide the nominal herbicide concentrations. For foliar applications, herbicides were applied using a carbon dioxide- (CO_2) pressurized sprayer at a spray volume of 187 L ha^{-1}. A nonionic surfactant[8] was added to the spray mixture at a rate of 1% v/v. Barriers (122 cm high) were placed around each tank during applications to prevent herbicide drift between treatments. After 24 h, the water volume in each tank was replaced with clean water to remove any remaining herbicide from the tanks for both submersed and foliar applications. Untreated reference tanks were included to assess plant growth in the absence of herbicide application.

Visual percent control of treated plants, as compared to untreated reference plants, was rated weekly for the duration of the study. Percent control ratings are reported though a formal statistical analysis was not completed. At 3 and 6 wk after treatment (WAT), viable flowering rush was harvested (3 pots harvest $time^{-1}$) and separated into shoot and root and rhizome biomass (root and rhizome biomass were not separated and thus analyzed together as below-ground tissue). Biomass was then dried and weighed in a similar fashion to pretreatment samples. Shoot and root and rhizome biomass for both submersed and foliar treatments were compared to the untreated reference plants to assess herbicide efficacy using a one-way analysis of variance (ANOVA). If assumptions of normality were not met, data were analyzed using the nonparametric Kruskal–Wallis test based on ranks. If treatment effects were significant ($P \leq 0.05$), means were separated with the Student–Newman–Keuls (SNK) *post hoc* test.

RESULTS AND DISCUSSION

At 3 WAT (11 wk of growth) and 6 WAT (14 wk of growth), shoot mass in the untreated references was decreasing, and had declined by 20 and 69%, respectively, compared to pretreatment levels (Figure 1A). In contrast, root and rhizome mass only declined by 14 and 29% at the same harvest intervals (Figure 1B). Flowering rush exhibits this trend of shoot decline preceding the decline in root and rhizome tissue (Hroudová and Zákravský 1993, Madsen et al. 2011).

Only foliar applied herbicides resulted in >50% control of flowering rush (Table 1). Reduction of shoot biomass occurred 3 WAT with foliar applications of imazapyr [(±)-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-3-pyridinecarboxylic acid] combined with glyphosate [N-(phosphonomethyl)glycine], 2,4-D plus triclopyr, and aminopyralid (4-amino-3,6-dichloro-2-pyridinecarboxylic acid) (Figure 1A). By 6 WAT, all treatments significantly decreased shoot biomass. A 50% reduction occurred with triclopyr and aminopyralid, whereas a > 80% reduction occurred with 2,4-D combined with triclopyr, imazamox, and imazapyr. The addition of glyphosate with either imazamox or imazapyr did not improve shoot or root and rhizome control compared to the same products applied alone (Figure 1A and 1B).

After foliar herbicide applications, reductions in root and rhizome biomass followed similar trends as the shoot biomass, whereas triclopyr, 2,4-D plus triclopyr, and aminopyralid significantly reduced root and rhizome biomass as soon as 3 WAT. Decreases in root and rhizome biomass were not evident until 6 WAT for plants treated with glyphosate and imazapyr. In a similar controlled experiment, glyphosate activity on wild taro [*Colocasia esculenta* (L.) Schott] following foliar applications took longer to observe than that of diquat, 2,4-D, or triclopyr (Nelson and Getsinger 2000).

Submersed applications did not result in reductions of either shoot or root and rhizome biomass in this study. Shoot biomass between submersed treatments ranged from 10.5 to 8.2 g dry weight (DW) pot^{-1}, respectively, for the 3 and 6 WAT harvests, with no treatment offering better control when compared to untreated plants. Similarly, root and rhizome biomass in all treatments were not different from untreated plants, where biomass ranged from 42.8 to 65.6 g DW pot^{-1}. We propose that lack of efficacy using auxin herbicides was due in large part to the 24-hr exposure time used and plant morphology (i.e., targeting emergent plants); or that submersed applications of auxin herbicides are not as effective on flowering rush as other treatments. It was reported in a similar study that submersed applications of 2,4-D and triclopyr only reduced shoot and root biomass by approximately 50% using maximum label concentrations and a 24-h exposure time (Poovey et al. 2013).

Plant phenology is another plausible explanation for the differences in efficacy observed between foliar and submersed herbicide applications in our study. Flowering rush had begun flowering prior to herbicide applications, which indicates that plants had attained maximum growth (as supported by pretreatment biomass), and shoot mass in untreated reference plants was visually decreasing by 3 WAT. The decrease in biomass of the untreated reference plants after flowering indicates that senescence had begun; by 6 WAT, biomass in untreated reference tanks was much lower than pretreatment levels suggesting plants were not actively growing and thus did not uptake a lethal herbicide dose. In riverine systems where flowering rush is problematic, submersed applications might not be an early season option due to high water flow and reduced herbicide contact times; therefore, managers might have to rely on foliar applications later in the year on more mature plants. The late-season application strategy has been recommended when using phloem-mobile systemic herbicides on other plant species (Decruyenaere and Holt 2001). Giant reed (*Arundo donax* L.) treated with glyphosate in September and October had the lowest proportion of living stems 1 yr later as compared to other treatment times (Spencer et al. 2011). Applications of glyphosate, imazapyr, and glyphosate plus imazapyr on giant reed were reported to be more effective when applied in the fall (Bell 2011). Smith et al. (1993) suggested that late-fall applications of glyphosate might be more efficacious on torpedo grass (*Panicum repens* L.) than summer applications due to shifts in resource allocation to rhizomes.

The current study indicates that 2,4-D, triclopyr, and combinations of 2,4-D and triclopyr are effective as foliar applications at reducing root and rhizome biomass of emergent flowering rush and expands the list of herbicides beyond glyphosate and imazapyr that could potentially be used for late-season control of flowering rush. Given the

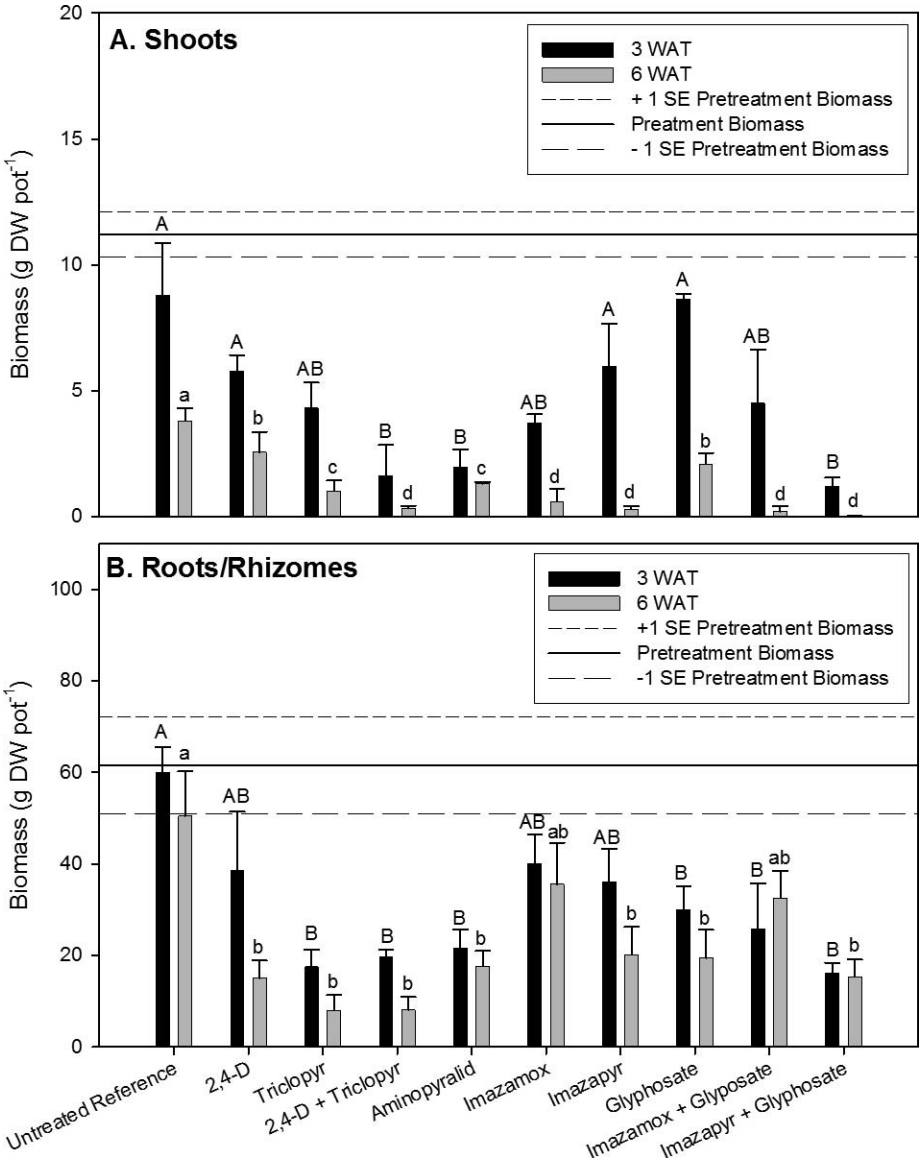

Figure 1. Biomass (mean ± 1 standard error [SE], g dry weight [DW], $n = 3$) of triploid flowering rush collected from Detroit Lake, MN, and grown in mesocosms in Starkville, MS, at 3 and 6 wk after treatment (WAT) following late season foliar applications of herbicides. Results are presented for (A) shoots and (B) roots and rhizomes. Treatments with the same letter do not significantly differ from one another (Student–Neuman–Keuls [SNK], $P < 0.05$). Solid horizontal lines represent mean pretreatment biomass; dashed lines above and below the solid line represent ± 1 SE.

initial planting of a 10-cm rhizome, the allocation of biomass in this study was nearly 7:1 in favor of root and rhizome biomass by 3 WAT. The large input of resources to belowground tissue would have tremendous impacts on the expectation for control, and therefore, the translocation of herbicides becomes a significant issue. Herbicide applications that can reduce root and rhizome biomass can offer longer-term control of flowering rush through limiting recruitment in following years, although multiple herbicide applications would be necessary. When plants emerge and begin flowering, foliar herbicide applications would be recommended to reduce both emergent shoot and root and rhizome biomass. It would not be recommended to use submersed applications with the herbicides evaluated once flowering rush emerges from the water column; other herbicide formulations such as diquat are better at controlling submersed flowering rush (Madsen et al. 2012). Based on these data and results of previous studies, improving control of flowering rush populations will likely require linking herbicide formulation and application method (submersed vs. foliar) with plant growth stage.

SOURCES OF MATERIALS

[1]Osmocote®, The Scotts Company, Marysville, OH.
[2]DMA 4 IVM®, Dow AgroSciences, Indianapolis, IN.
[3]Renovate3®, SePRO Corporation, Carmel, IN.
[4]Clearcast®, BASF Corporation, Research Triangle Park, NC.
[5]Milestone®, Dow AgroSciences, Indianapolis, IN.
[6]Habitat®, BASF Corporation, Research Triangle Park, NC.
[7]Rodeo®, Dow AgroSciences, Indianapolis, IN.
[8]Cygnet Plus®, Cygnet Enterprises, Flint, MI.

ACKNOWLEDGEMENTS

This research was conducted under the U.S. Army Corps of Engineers Aquatic Plant Control Research Program. Additional support for this work was provided by the Pelican River Watershed District and the Aquatic Ecosystem Restoration Foundation. The authors thank C. McLaurin for technical assistance. Reviews of this manuscript were provided by C. Welling and L. Glomski. Permission was granted by the Chief of Engineers to publish this information. Citation of trade names does not constitute endorsement or approval of the use of such commercial products.

LITERATURE CITED

Bell CE. 2011. Giant reed (*Arundo donax*) response to glyphosate and imazapyr. J. Aquat. Plant Manage. 49:111–113.

Countryman WD. 1970. The history, spread and present distribution of some immigrant aquatic weeds in New England. Hyacinth Control J. 8:50–52.

Decruyenaere JG, Holt JS. 2001. Seasonality of clonal propagation in giant reed (*Arundo donax*). Weed Sci. 49:760–767.

Getsinger KD, Fox AM, Haller WT. 1996. Herbicide application technique development for flowing water: Summary of research accomplishments. MP A-96-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. 16 pp.

Getsinger KD, Netherland MD. 1997. Herbicide concentration/exposure time requirements for controlling submersed aquatic plants: Summary of research accomplishments. MP A-97-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. 18 pp.

Hroudová Z, Zákravský P. 1993. Ecology of two cytotypes of *Butomus umbellatus* III. Distribution and habitat differentiation in the Czech and Slovak Republic. Folia Geobot. Phytol. 28:425–435.

Lui K, Thompson FL, Eckert CG. 2005. Causes and consequences of extreme variation in reproductive strategy and vegetative growth among invasive populations of a clonal plant, *Butomus umbellatus* L. (Butomaceae). Biol. Invasions 7:427–444.

Madsen JD. 1997. Seasonal biomass and carbohydrate allocation in a southern population of Eurasian watermilfoil. J. Aquat. Plant Manage. 35:15–21.

Madsen JD, Marko MD, Cheshier JC, Olson C. 2011. Flowering rush in the Detroit Lakes Chain Becker County, Minnesota. Report to the Pelican River Watershed District. Starkville (MS): Mississippi State University. 19 pp.

Madsen, JD, Sartain B, Turnage G, Marko M. 2013. Herbicide trials for the management of flowering rush in Detroit Lakes, Minnesota for 2012. Geosystems Research Institute Report #5059, Mississippi State University, Starkville, MS. 59 pp.

Madsen JD, Wersal RM, Marko MD, Skogerboe JG. 2012. Ecology and management of flowering rush (*Butomus umbellatus*) in the Detroit Lakes, Minnesota. Geosystems Research Institute Report #5054, Mississippi State University, Starkville, MS. 43 pp.

Marko M., Madsen JD, Olson C, Smith R. 2012. Ecology of flowering rush (*Butomus umbellatus*) in Detroit Lakes, Becker County, Minnesota. Letter report to the Pelican River Watershed District, Concordia College, Moorhead, MN. August 2012. 19 pp.

Nelson LS, Getsinger KG. 2000. Herbicide evaluations for control of wild taro. J. Aquat. Plant Manage. 38:70–72.

Poovey AG, Mudge CR, Getsinger KD, Sedivy H. 2013. Control of submersed flowering rush with contact and systemic aquatic herbicides under experimental conditions. J. Aquatic. Plant Manage. 51:53–61.

Poovey AG, Mudge CR, Thum RA, James C, Getsinger KD. 2012. Evaluations of contact aquatic herbicides for controlling two populations of submersed flowering rush. J. Aquatic. Plant Manage. 50:48–54.

Rice P, Dupuis V, Mitchell A. 2009. Results in the second summer after foliar application of herbicides to flowering rush. Report to the Montana Noxious Weed Trust Fund. Bozeman (MT): Montana State University. 7 pp.

Smith BE, Shilling DG, Haller WT, MacDonald GE. 1993. Factors influencing the efficacy of glyphosate on torpedograss (*Panicum repens* L.). J. Aquat. Plant Manage. 31:199–202.

Spencer DF, Ksander GG, Tan W, Liow PS, Whitehand LC. 2011. Influence of application timing on the impact of glyphosate on giant reed (*Arundo donax*). J. Aquat. Plant Manage. 49:106–110.

Wersal RM, Cheshier JC, Madsen JD, Gerard PD. 2011. Phenology, starch allocation, and environmental effects on *Myriophyllum aquaticum*. Aquat. Bot. 95:194–199.

Wersal RM, Madsen JD, Cheshier JC. 2013. Seasonal biomass and starch allocation of *Phragmites australis* (Haplotype I) in southern Alabama, USA. Invasive Plant Sci. Manage. 6:140–146.

Woolf TE, Madsen JD. 2003. Seasonal biomass and carbohydrate allocation patterns in Southern Minnesota curlyleaf pondweed populations. J. Aquat. Plant Manage. 41:113–118.