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Using contact herbicides for control of duckweed and watermeal with implications for management

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ABSTRACT

Floating plants like duckweed (*Lemna minor* L.) and watermeal (*Wolffia columbiana* Karst) are becoming widespread problems in waterways in the United States. Both species can be difficult to control as they are capable of rapidly recolonizing a site after management efforts have been implemented. Unaffected plants can drift into the site or, due to their small size, plants are missed during herbicide applications. Flumioxazin and diquat are two contact herbicides that are recommended for managing watermeal and duckweed. Although published literature exists in support of diquat use, there is little published literature for flumioxazin use on watermeal and no published literature in support of its use in managing duckweed. Greenhouse, mesocosm, and field trials were conducted to evaluate the efficacy of both herbicides on watermeal and duckweed in order to document flumioxazin efficacy in the literature. Foliar applications of flumioxazin (105 g ai ha^{-1}, 211 g ai ha^{-1}, and 422 g ai ha^{-1}) and diquat (2,255 g ai ha^{-1}) were evaluated in the greenhouse and mesocosm trials. Based on results from the greenhouse and mesocosm trials only the 422 g ai ha^{-1} rate of flumioxazin and diquat were evaluated in separate ponds. At 4 wk after treatment, all rates of flumioxazin reduced duckweed biomass compared to nontreated reference plants. Watermeal control was more variable in that only the 422 g ai ha^{-1} flumioxazin treatment provided a significant reduction in biomass in the greenhouse study, but no reductions were observed in the mesocosm study. When these herbicides were applied to ponds, flumioxazin and diquat reduced floating plant biomass by 96 and 93%, respectively. However, when managing a mixed community of floating plants that contains watermeal using either diquat or flumioxazin, managers would likely release watermeal as it was the only plant that survived the pond trials. A follow-up application would be needed to eliminate watermeal from the water body.

Key words: chemical control, diquat, *Lemna minor*, nuisance vegetation, *Wolffia Columbiana*.

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INTRODUCTION

Floating aquatic plants are increasingly problematic in waterways in the southern United States (Barrett 1989, Pfingsten et al. 2019, Thayer et al. 2019, Turnage and Shoemaker 2018). Nuisance aquatic plant problems are often exacerbated with increased nutrient inputs into water bodies from point and nonpoint sources (Burkholder et al. 1992, Carpenter et al. 1998, Carey and Migliaccio 2009). Common duckweed (*Lemna minor* L.; hereafter duckweed) and watermeal (*Wolffia columbiana* Karst) are two such floating aquatic plants that thrive in high-nutrient environments (Vermaat and Hanif 1998). Both species primarily reproduce through vegetative means (Claus 1972, Bernard et al. 1990) and are capable of rapid reproduction. Duckweed can double in frond density in approximately 5 d (Claus 1972) while watermeal can double in 2 to 3 d (Bernard et al. 1990). Dense infestations of duckweed and watermeal can shade submersed aquatic plants and cause oxygen depletions in the water column (Parr et al. 2002) resulting in fish kills (Lewis and Bender 1961). Currently, there are no management recommendations that result in consistent and predictable watermeal control. Additionally, floating plants like duckweed and watermeal can rapidly recolonize a site after management through immigration of new plants by water currents, birds, and animals.

Foliar application of diquat is one of the most frequently used treatments for management of watermeal and duckweed (Langeland et al. 2002, Mudge et al. 2007, Wersal and Madsen 2009, 2012). Langeland et al. (2002) applied foliar treatments of diquat (551, 1,127, and 1,679 g ai ha^{-1}) to duckweed and reported 92 to 100% necrotic tissue at 14 d after treatment (DAT). Wersal and Madsen (2009) reported 100% reduction of duckweed and watermeal 28 DAT using foliar (4,500 g ai ha^{-1}) applications of diquat.

In-water applications of diquat have also been evaluated on duckweed, and when applied at 0.5 and 1.0 mg L^{-1}, provided 66 and 88% biomass reduction, respectively, when averaged over three ponds 4 mo after treatment (MAT) (Blackburn and Weldon 1965). In the same study, 99 to 100% reduction of watermeal was achieved when diquat was applied at 1.0 mg L^{-1} and 0.5 mg L^{-1}, respectively, 4 MAT (Blackburn and Weldon 1965). The aforementioned diquat concentrations are above the labeled limit for diquat. When duckweed and watermeal were exposed to the maximum label rate (0.37 mg L^{-1}) of diquat it resulted in 100% control of duckweed, but no control of watermeal (Wersal and Madsen 2009). In contrast, submersed diquat applications of 0.2 and 0.4 mg L^{-1} resulted in 84 and 94% control of watermeal 21 DAT (Mudge et al. 2007). The systemic herbicides fluridone and penoxsulam have also been evaluated as a static exposure at the mesocosm scale with some success for management of both species (Cheshier et al. 2011). Both of these herbicides are typically applied at low rates (15 to 75 μg L^{-1}) and require long exposure times (> 30 DAT) before symptomology is evident, which may not be achievable in some water bodies (Kay 1991, Cheshier et al 2011).

Flumioxazin was registered for use in aquatic plant management in 2010. Submersed applications of flumioxazin targeting concentrations of 0.2 and 0.4 mg L^{-1} provided 94% reductions in watermeal at 21 DAT (Mudge et al. 2007). While the herbicide has shown success at reducing watermeal in small-scale trials, rapid degradation can be expected at the field scale, especially when water pH is above 8 (Mudge and Haller 2010). Additionally it is widely accepted that flumioxazin is efficacious on duckweed (Enloe et al. 2018, Anonymous 2020); however, to our knowledge there are no peer-reviewed manuscripts demonstrating this efficacy. Additionally, Mudge et al. (2007) is the only small-scale study that has evaluated flumioxazin on watermeal. The objectives of this study were to determine the efficacy of foliar-applied flumioxazin rates for reduction of duckweed and watermeal biomass in greenhouse and mesocosm evaluations, and to verify effective flumioxazin rates from the greenhouse and mesocosm evaluations in small ponds.

MATERIALS AND METHODS

Greenhouse trial

A greenhouse trial was conducted during the summers of 2017 and 2018 at the Mississippi State University (MSU) Aquatic Plant Research Facility (APRF). In total, 40 aquariums were used for these trials. Watermeal was collected from stock cultures maintained at the MSU-APRF and used to inoculate 20 40-L aquariums. Duckweed was collected locally from a pond in Oktibbeha County, MS, and used to inoculate 20 aquariums in the same facility. Aquariums were filled with well water amended weekly with fertilizer[1] at a rate of 30 mg L^{-1} of water to stimulate plant growth. After inoculation, plants were given 1 mo to establish. Following the establishment period the water surface in all 20 aquariums containing watermeal and all 20 aquariums containing duckweed was completely covered. Prior to herbicide treatment, biomass was collected from each aquarium using a polyvinyl chloride (PVC; 0.002 m^2) sampling device (Wersal and Madsen 2009).

The PVC device was constructed using a 5.1-cm PVC ball valve glued to a 61-cm piece of 5.1-cm PVC pipe. The ball valve was opened and pushed through the plant mat in each tank, forcing the plants up into the 5.1-cm pipe. The ball valve was then closed while submersed, keeping the plants in the sampler. A coffee filter was fitted into a hand-held metal colander and held over the end of the sampler to catch plant samples when the valve was opened. Water was then run through the sampler to rinse remaining plants into the filter. Collected biomass (filter and plant sample) were placed in labeled paper bags and dried in a forced air oven at 70 C for 5 d. After drying, three unused filters were randomly selected from the package and weighed to establish a mean weight for the filters. The filters containing the plant samples were then weighed and then the difference between the samples and the filter mean was calculated. The calculated value was divided by the area of the sampling device (0.002 m^2) to estimate dry weight (g DW m^{-2}) of biomass for each species.

Following the pretreatment, harvest plants were exposed to one of four foliar herbicide treatments: 105 g ai ha^{-1} flumioxazin,[2] 211 g ai ha^{-1} flumioxazin, 422 g ai ha^{-1} flumioxazin, or 2,255 g ai ha^{-1} diquat.[3] A nontreated reference was also included to make comparisons in the absence of herbicide. All herbicide treatments included a nonionic oil concentrate surfactant[4] at a 0.5% v/v. Foliar applications were administered using a CO_2-pressurized backpack sprayer at a spray volume equivalent of 935 L ha^{-1}. Water used in the herbicide spray solution was buffered to a pH of 6.5 to 7.0 before herbicide mixing to ensure that flumioxazin would not degrade prior to treatment. Treatments were randomly assigned to aquaria and each treatment was replicated four times.

Four WAT, a biomass sample was collected from each aquarium and processed in the same manner as pretreatment specimens. Samples were analyzed using a mixed model to determine if significant differences existed in biomass between herbicide treatments. Treatment was considered a fixed variable while year of experiment (2017 and 2018) was considered a random variable. Differences in means were further separated using a Tukey's post hoc test. All statistical tests were conducted at the $P \leq 0.05$ significance level in the statistical software R using the lmerTest and rcompanion packages (R Core Team 2018).

Mesocosm trial

The mesocosm trial was conducted at the Lonza Aquatic Plant Research Facility in Alpharetta, GA, from August to September 2017. Duckweed and watermeal were obtained from cultures located in the facility. Both species were taken from their respective culture tanks and placed into each of 20 378.5-L tanks (20 for each species, 40 tanks total) to cover 75% of the water surface. The water depth in each tank was filled to a depth of 40 cm. Water was amended weekly with 30 mg L^{-1} of fertilizer[1] to maintain plant growth. Plants were allowed to grow for approximately 2 wk or until plant coverage in all tanks was 100%. Pretreatment biomass (one sample per tank) was harvested using the PVC sampling device as outlined in Wersal and Madsen (2009) and used in the greenhouse trials. Biomass from each tank was placed in a paper bag, dried at 50 C for at least 48 h, and then weighed to determine dry weight.

After the acclimation period and pretreatment harvest, plants in each mesocosm were treated using a foliar spray with the same herbicides and rates as previously described in the greenhouse trials. Treatments were applied using a CO_2 backpack sprayer with a single nozzle. Water was used as a carrier to deliver a foliar spray at a total spray volume of 935 L ha^{-1}. All foliar sprays included a surfactant[5] applied at a 0.5% v/v. At 25 DAT, a biomass sample was harvested from each tank, using the same methodology as the pretreatment harvest. Samples were dried at 50 C for at least 48 h, and then weighed to determine dry weight biomass. Differences between treatments were analyzed using a Kruskal-Wallis test. If differences were observed, then treatment means were separated using a Dunn's All-Pairwise Comparison test. Analyses were conducted at a $P \leq 0.05$ significance level.

Field trial

Two ponds in Smith County, MS, were selected for a field trial using the best performing treatments from the greenhouse and mesocosm studies. Pond 1 was approximately 0.3 ha in size and infested with watermeal and duckweed at 80 and 20% coverage, respectively. Pond 2 was approximately 0.4 ha in size and infested with watermeal, duckweed, and mosquitofern (*Azolla caroliniana* Willd.) at 40, 40, and 20% coverage, respectively. Prior to herbicide applications, 15 pretreatment samples were randomly collected and processed from each pond in the same manner as the greenhouse and mesocosm biomass sampling. Given the density and small size of these species no effort was made to separate species from each other when collecting biomass samples.

After collection of pretreatment specimens, Pond 1 received an application of 422 g ai ha^{-1} flumioxazin and Pond 2 received an application of 2,255 g ai ha^{-1} diquat. A new protein-based surfactant[6] was added to each treatment at a rate of 0.5% v/v. The adjuvant is a combination of synergistic proteins (polypetides) and surfactants to improve control of both aquatic vasuclar plants and algae (Goldfeld et al. 2015, Ratajczyk et al. 2018). Treatments were made using a 95-L tank outfitted with a Fimco high-performance pump[7] (9.1 L min^{-1}) installed in a small fishing boat. A boom was attached to the sprayer that extended to the side of the boat; at the end of the boom was a fan nozzle capable of spraying a 4.5-m swath alongside the boat. The boat was systematically navigated over each pond until the entire surface had been treated with herbicide. At 4 WAT, 15 biomass samples were again randomly collected from each pond and processed in the same manner as pretreatment specimens. A paired t test was used to compare pretreatment and posttreatment biomass within each pond at the $P \leq 0.05$ significance level (R Core Team 2018).

RESULTS AND DISCUSSION

Greenhouse trial

Diquat resulted in 100% biomass reduction of duckweed when compared to nontreated reference plants. Flumioxazin applied at 422 g ai ha^{-1}, 211 g ai ha^{-1}, and 105 g ai ha^{-1} resulted in 80, 90, and 61% biomass reduction, respectively, when compared to nontreated reference plants (Figure 1). Watermeal biomass was reduced 78% by diquat and 43% by flumioxazin when applied at 422 g ai ha^{-1} when compared to nontreated reference plants (Figure 1). The 105-g ai ha^{-1} and 211-g ai ha^{-1} flumioxazin applications did not reduce

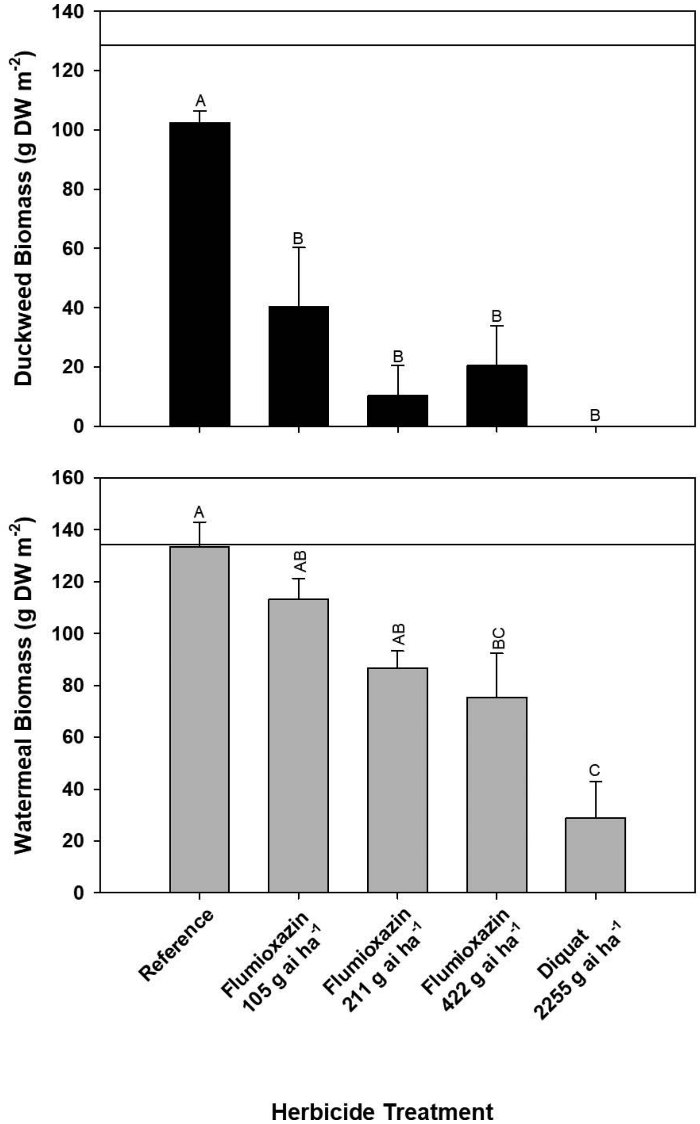

Figure 1. Mean (± 1 SE) biomass of common duckweed and watermeal four weeks after application of flumioxazin or diquat under greenhouse conditions in Starkville, MS. Bars sharing the same letter are not different at a $P \leq 0.05$ significance level. The solid lines represent pretreatment biomass.

watermeal biomass when compared to reference plants (Figure 1).

Mesocosm trial

Biomass reduction of duckweed was 100% when both herbicides were applied regardless of the rates tested (Figure 2). These results indicate that duckweed is highly susceptible to flumioxazin when applied at 105 g ai ha^{-1} which is one-fourth of the maximum labeled rate. The diquat rate used as a comparison is half the maximum label rate and would be the minimum amount necessary for > 90% reduction in duckweed biomass (Wersal and Madsen 2009, 2012). When diquat was reduced to 560 g ai ha^{-1} it did not result in reductions in duckweed biomass even when

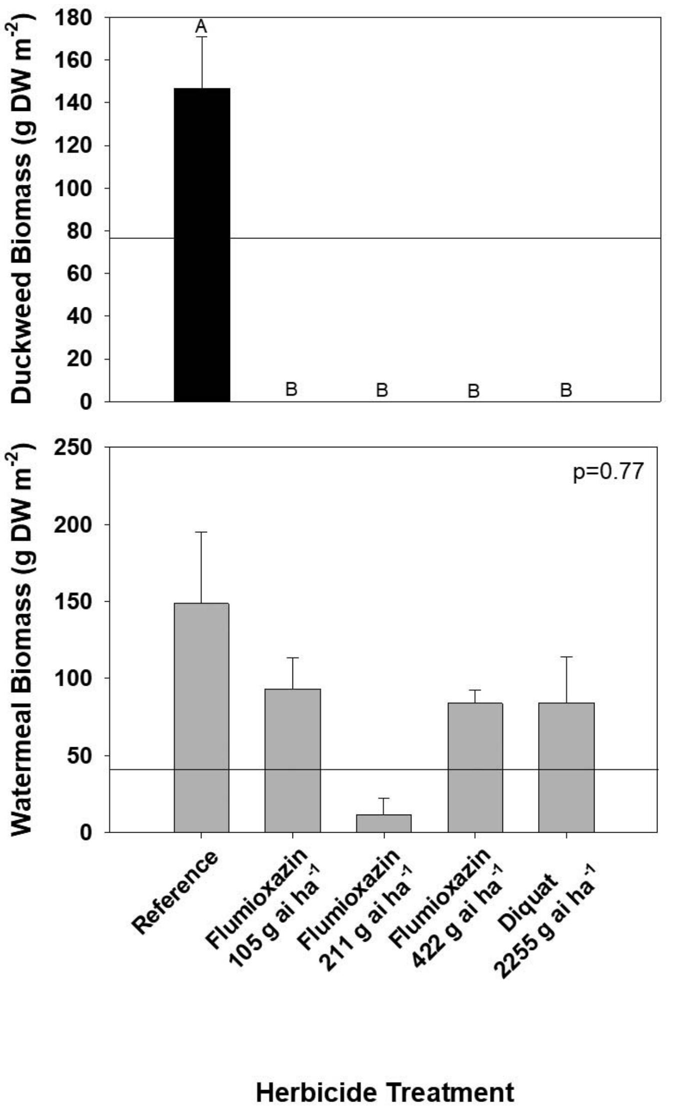

Figure 2. Mean (± 1 SE) biomass of common duckweed and watermeal 25 d after application of flumioxazin or diquat under mesocosm conditions in Alpharetta, GA. Bars sharing the same letter are not different at a $P \leq 0.05$ significance level according to a Dunn's All Pairwise Comparison test. The solid lines represent pretreatment biomass.

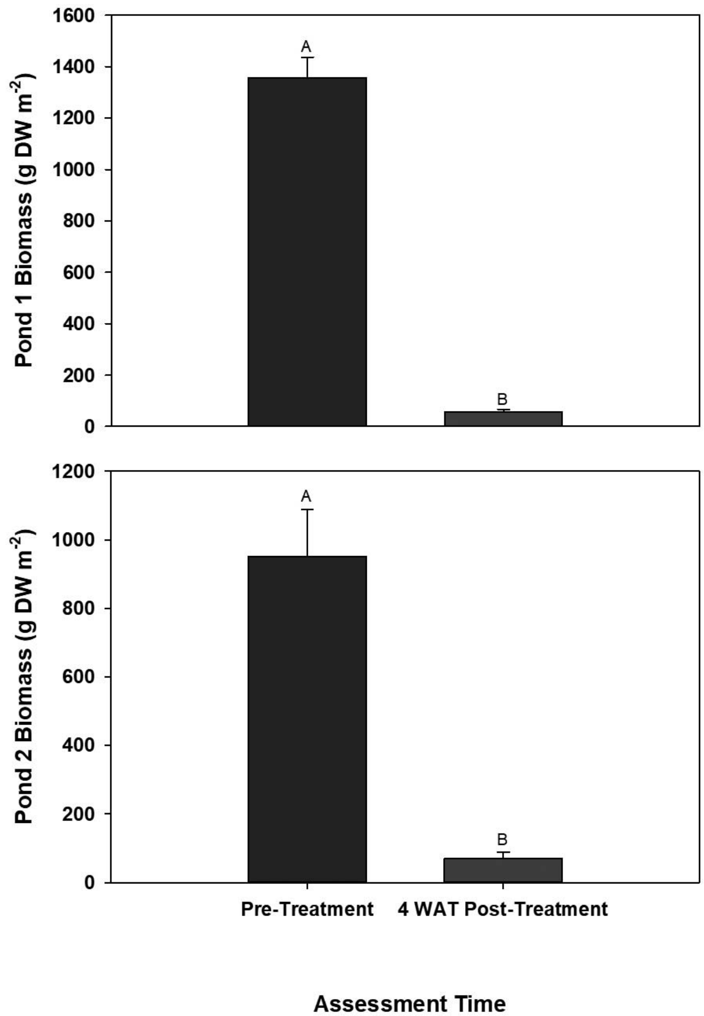

Figure 3. Mean (± 1 SE) biomass of floating plants (common duckweed and watermeal: Pond 1; common duckweed, watermeal, and mosquitofern: Pond 2) in two Mississippi ponds 4 wk after flumioxazin and diquat treatments. Pond 1 received 0.422 g ai ha^{-1} flumioxazin and Pond 2 received 2255 g ai ha^{-1} diquat. Bars sharing the same letter are not different at the $P \leq 0.05$ significance level according to a paired *t* test. Analyses were done within pond between sampling time.

combined with carfentrazone-ethyl under similar test conditions (Wersal and Madsen 2012).

In contrast, watermeal was less sensitive to the herbicide applications at the conclusion of 25 d. Neither herbicide nor any of the rates tested resulted in significant ($P = 0.77$) biomass reduction when compared to reference plants (Figure 2). The lack of sensitivity of watermeal to herbicide applications at the mesocosm level could be attributed to its reproductive strategies and production of daughter fronds. Both watermeal and duckweed produce daughter fronds from existing vegetation (Claus 1972, Bernard et al. 1990, White and Wise 1998), but daughter fronds of watermeal are initially protected in a budding cavity within the parent plant (Bernard et al. 1990, White and Wise 1998). Therefore, watermeal daughter fronds would not be impacted by an application until they have been released from the budding cavity of the parental frond. Duckweed produces daughter fronds, but unlike watermeal, the fronds are exposed to the aquatic environment throughout the developmental process and are capable of receiving herbicide through the exposed upper and lower leaf surfaces (Ice and Couch 1987, Meijer and Sutton 1987), making them more susceptible to treatment.

Field trial

Flumioxazin reduced ($P < 0.01$) the overall biomass of floating plants in Pond 1 (watermeal and duckweed) by 96% at 4 WAT (Figure 3). Diquat reduced ($P < 0.01$) the overall biomass of floating plants in Pond 2 (watermeal, duckweed, and mosquitofern) by 93% at 4 WAT (Figure 3). Even though species were not separated for analysis during the field trial, it was interesting to note that at 4 WAT the only species to have survived the herbicide treatments in both ponds was watermeal. It was the only living plant harvested posttreatment. Therefore, it could recolonize both ponds if follow-up applications were not made.

There are several plausible hypotheses for the observed reduced sensitivity of watermeal to flumioxazin (all of which would need further testing). Spraying over the top of watermeal, or the the action of the boat wake during application, may cause some of the fronds to be physically pushed underwater. Once underwater the spray solution would be washed off the fronds and thus result in reduced efficacy. Watermeal has a rapid growth rate and unaffected plants can quickly recolonize a treated area. On average, the life span of a watermeal plant is 17 ± 1 d, and the average number of plants it can produce during this time is 11 ± 1 plants with a maximum of 15 fronds per plant (Bernard et al. 1990). This life span and growth capacity results in a doubling time of 2 to 3 d which is faster than duckweed (Bernard et al. 1990). Again, if daughter fronds of watermeal plants are protected in a budding cavity this would allow new plants to escape exposure to a herbicide application both spatially and temporally. Ultimately, if plants were missed, or the spray solution washed off during the initial application; over a 4-wk study there would be sufficient time for watermeal fronds to double their biomass several times and recover the water surface.

Results from these studies indicate that duckweed is in fact very sensitive to flumioxazin at application rates as low as 105 g ai ha^{-1}, which to our knowledge is an application rate that has not been previously evaluated. Even in a mixed community, duckweed was controlled by applications of diquat or flumioxazin. Watermeal, however, was more difficult to control with either herbicide and current results corroborate previous research that control will be variable. Flumioxazin did provide 70 to 90% reduction in aerial coverage when estimated visually between 7 and 21 DAT in the mesocosm study; however, by the end of that study there was no significant reduction in biomass. Under field conditions where watermeal is present, herbicide applications of the herbicides tested may release watermeal from competitive pressure with other species allowing it to spread. If watermeal growth is dense, multiple applications of diquat or flumioxazin will be needed to get complete control of nuisance growth.

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SOURCES OF MATERIALS

[1]Miracle-Gro® water soluable all purpose plant food, The Scotts Company, P.O. Box 606, Marysville, OH 43040.

[2]Clipper SC® aquatic herbicide, Nufarm Americas Inc., 11901 South Austin Ave, Alsip, IL 60803.

[3]Harvester® aquatic herbicide (diquat dibromide), Applied Biochemists, 1400 Bluegrass Lakes Pkwy, Alpharetta, GA 30004.

[4]Kammo Plus™ nonionic oil concentrate adjuvant/masking agent, Helena Chemical Company, 225 Schilling Blvd, Suite 300, Collierville, TN 38017.

[5]AB™ aquatic adjuvant and nonionic surfactant, Applied Biochemists, 1400 Bluegrass Lakes Pkwy, Alpharetta, GA 30004.

[6]Amp↑™ activator, Applied Biochemists, 1200 Bluegrass Lakes Pkwy, Alpharetta, GA 30004.

[7]Fimco High Performance 2.4 GPM Bypass 12V Pump, Fimco Industries, North Sioux City, SD

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