J. Aquat. Plant Manage. 47: 59-62

Combinations of Diquat and a Methylated Seed Oil Surfactant for Control of Common Duckweed and Watermeal

RYAN M. WERSAL[1] AND J. D. MADSEN[1,2]

INTRODUCTION

Common duckweed (*Lemna minor* L.; hereafter referred to as duckweed) and watermeal (*Wolffia* spp.) are two floating aquatic plants that can cause severe problems in small water bodies, especially in the southern United States. Duckweed and watermeal infestations can reduce the use and aesthetics of small water bodies, may impact native submersed plant growth, and may be responsible for oxygen depletion in the water column (Hillman 1961, Parr et al. 2002). These nuisance problems currently do not have management recommendations that produce predictable results, particularly for watermeal. The aquatic herbicide diquat (6,7-dihydrodipyrido [1,2-a:2',1'-c] pyrazinedium dibromide) is one of the most frequently prescribed herbicides for control of duckweed and watermeal. A previous study reported 95% control of duckweed using diquat with a silicone surfactant (Langeland et al. 2002). Watermeal treated with a subsurface application of diquat at 0.40 mg ai L^{-1} resulted in 94% control 21 days after treatment (DAT) in a greenhouse study in

[1]GeoResources Institute, Mississippi State University, Mississippi State, MS 39762-9652.

[2]Corresponding author, E-mail: jmadsen@gri.msstate.edu.

[3]Miracle-Gro® Water Soluable All Purpose Plant Food, The Scotts Company, P. O. Box 606 Marysville, OH 43040.

[4]Reward® Landscape and Aquatic Herbicide, Syngenta Professional Products P.O. Box 18300 Greensboro, NC 27419.

[5]Sunwet®, Brewer International, P. O. Box 690037, Vero Beach, FL 32969.

Received for publication June 18, 2008 and in revised form August 4, 2008.

Florida (Mudge et al. 2007). Duckweed was found to be more susceptible to diquat than watermeal in laboratory and small pond trials; however, control of these species under field conditions has been highly variable (Blackburn and Weldon 1965).

A typical recommendation for both species is to apply diquat as a foliar treatment mixed with a surfactant (Syngenta Corp. 2007). Methylated seed oil could offer increased efficacy through aiding herbicide movement across leaf cuticles by penetrating cuticular wax on the leaf surfaces, thereby enhancing herbicide uptake into target plants (Hazen 2000). To date, there is little published literature on the use of diquat for control of duckweed and watermeal, with or without a surfactant, or data on application methods. Our objectives were to: (1) evaluate the use of a methylated seed oil surfactant with diquat to increase control of duckweed and watermeal; and (2) compare diquat efficacy as a subsurface and foliar application against duckweed and watermeal. This study recommends whether the addition of methylated seed oil increases herbicide efficacy on duckweed and watermeal. These data will be useful for developing control programs for duckweed and watermeal by pond managers, private applicators, and university extension service personnel.

MATERIALS AND METHODS

The study was conducted from August through September 2007 at the R.R. Foil Plant Science Research Center, Mississippi State University, Starkeville, Mississippi. The study was arranged in a completely randomized design with five treatments and four replications per treatment. Duckweed and watermeal were collected locally from small water bodies and placed into 150-L tanks. Tank dimensions were 0.9 by 0.7 by 0.3 m in depth and a total surface area of 0.6 m^2. Duckweed and watermeal were each planted in 20 tanks (40 total) to cover the water surface. Plants were allowed to acclimate for approximately two weeks prior to herbicide treatments. Water was amended with Miracle-Gro®[3] 15-30-15 fertilizer at a rate of 30 mg L^{-1} per week to maintain plant growth.

Following the acclimation period, plants were treated with diquat (Reward®[4]) with and without a 1% methylated seed oil surfactant (SunWet®[5]) mixed volume to volume. Foliar treatments consisted of 4.5 kg ai ha^{-1} with and without the methylated seed oil surfactant using a CO_2 pressurized backpack spray system at a spray volume of 935 L ha^{-1} (100 gal $acre^{-1}$). Subsurface treatments included aqueous concentrations (0.37 mg ai L^{-1}) of diquat with and without the methylated seed oil surfactant and were made by applying a concentrated aqueous solution to designated tanks. Subsurface applications were made to 95 L of water under static exposure. After treatment, tanks were rated for percent control in 10% increments from 0 (no control) to 100% (complete control) at 1, 3, 5, 7, 14, 21, and 28 days after treatment (DAT). At 28 DAT, two biomass samples were collected from each tank using a (0.002 m^2) PVC sampling device. The device was constructed using a 2 in (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 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.

Samples were dried, weighed, and converted to g DW m^{-2} based on the area of the sampling device. Control ratings and biomass data were subjected to Bartlett's test for homogeneity of variance to test the assumption of normality. Data met this assumption and, therefore, differences in control ratings and biomass were assessed using a one-way ANOVA with means separated using a Fisher's Protected LSD test. All analyses were conducted at a $p = 0.05$ level of significance using Statistix 8.0 (Analytical Software 2003).

RESULTS AND DISCUSSION

Common Duckweed

Foliar applications of diquat resulted in 100% control of duckweed by three DAT (Table 1). Similar control was achieved with subsurface applications by seven DAT. At seven DAT, all treatment methods and rates resulted in 100% control of duckweed, and this level of control was maintained to 28 DAT. There were no differences in control between the foliar and subsurface applications of diquat by five DAT; likewise, efficacy did not improve with the addition of a methylated seed oil surfactant. Biomass of duckweed in all treatments was different ($p < 0.01$) from untreated reference plants (Figure 1). Diquat offered complete control of duckweed by 28 DAT regardless of treatment method or the addition of a methylated seed oil surfactant. In a similar small-scale study, duckweed was controlled 99% 14 DAT using 4.6 kg ai ha^{-1} of diquat and a silicone surfactant (Langeland et al. 2002). Diquat applied at 0.10 mg ai L^{-1} also resulted in 100% chlorotic tissue seven DAT after treatment in a laboratory study by Blackburn and Weldon (1965), who also reported 100% control of duckweed four months after treatment in a small pond study using diquat at aqueous concentrations of 0.25 and 0.30 mg ai L^{-1}. They concluded that duckweed was more sensitive to diquat than watermeal. Our data corroborate this because duckweed was controlled at all rates and application methods, while diquat efficacy was only observed for foliar applications to watermeal.

The sensitivity of duckweed to diquat compared to watermeal may be due to permeability of both the adaxial and abaxial frond surfaces. A study of nutrient uptake by duckweed roots and fronds concluded that uptake occurred on the underside of the fronds (Ice and Couch 1987). Additionally, Meijer and Sutton (1987) found that nutrient uptake occurred through both the upper and lower frond surfaces. Therefore, diquat uptake in duckweed may occur, to some small extent, by passive diffusion from the water column, or from a foliar application that may further contribute to its susceptibility. Davies and Seaman (1968) reported that uptake of diquat in elodea appeared to consist of a rapid passive adsorption phase followed by a slower long-term uptake phase.

Table 1. Percent control of duckweed (*Lemna minor*) and watermeal (*Wolffia* spp.) following foliar and subsurface applications of diquat either with or without a methylated seed oil surfactant.

Diquat Treatment		Days After Treatment[ab]						
		1	3	5	7	14	21	28
		%						
Duckweed								
Untreated Reference		0 a	0 a	0 a	0 a	0 a	0 a	0 a
Foliar 4.5 kg ai ha^{-1}		80 b	100 c	100 b	100 b	100 b	100 b	100 b
Foliar 4.5 kg ai ha^{-1} + surfactant		90 b	100 c	100 b	100 b	100 b	100 b	100 b
Subsurface 0.37 mg ai L^{-1}		10 c	80 b	90 b	100 b	100 b	100 b	100 b
Subsurface 0.37 mg ai L^{-1} + surfactant		20 c	80 b	90 b	100 b	100 b	100 b	100 b
	LSD	10	5	5	1	1	1	1
Watermeal								
Untreated Reference		0 a	0 a	0 a	0 a	0 a	0 a	0 a
Foliar 4.5 kg ai ha^{-1}		70 b	90 c	100 c	100 c	100 c	100 b	100 b
Foliar 4.5 kg ai ha^{-1} + surfactant		70 b	100 c	100 c	100 c	100 c	100 b	100 b
Subsurface 0.37 mg ai L^{-1}		10 a	30 b	40 b	50 b	10 a	0 a	0 a
Subsurface 0.37 mg ai L^{-1} + surfactant		0 a	40 b	40 b	50 b	40 b	0 a	0 a
	LSD	13	12	11	25	27	3	3

[a]Means in a column followed by the same letter do not differ significantly at p = 0.05 according to Fisher's Protected LSD.
[b]Analyses were conducted within species and DAT.

Watermeal

Watermeal was less sensitive to diquat than duckweed, especially when exposed to the subsurface treatments. Subsurface treatments resulted in 50% control by seven DAT, and no control by 28 DAT when compared to untreated reference plants (Table 1). Foliar applications of diquat, either with or without the addition of a methylated seed oil, resulted in 100% control by five DAT. Biomass of watermeal was reduced ($p < 0.01$) with both foliar treatments when compared to untreated reference plants (Figure 1). Foliar applications at 935 L ha^{-1} with the CO_2 spray system likely had a smaller droplet size and required several passes of the spray tip to deliver the intended volume of spray solution. The smaller droplets may have allowed greater herbicide contact by not submersing plants, and repeated passes of the spray tip allowed for complete coverage of the watermeal mat resulting in greater herbicide efficacy. Under field conditions a high pressure sprayer is commonly used, resulting in larger spray droplets that tend to submerse watermeal plants when contacted, thus washing off the herbicide. Submersing plants during application under field conditions may be contributing to the variable response of watermeal to herbicide applications. However, further research is needed to evaluate the effects of spray volume and spray droplet size on floating plants. The addition of a surfactant to aid in leaf wetting or penetration is typically added the spray solution to increase herbicide contact with the target plant. However, the addition of the methylated seed oil did not increase diquat efficacy on watermeal in this study.

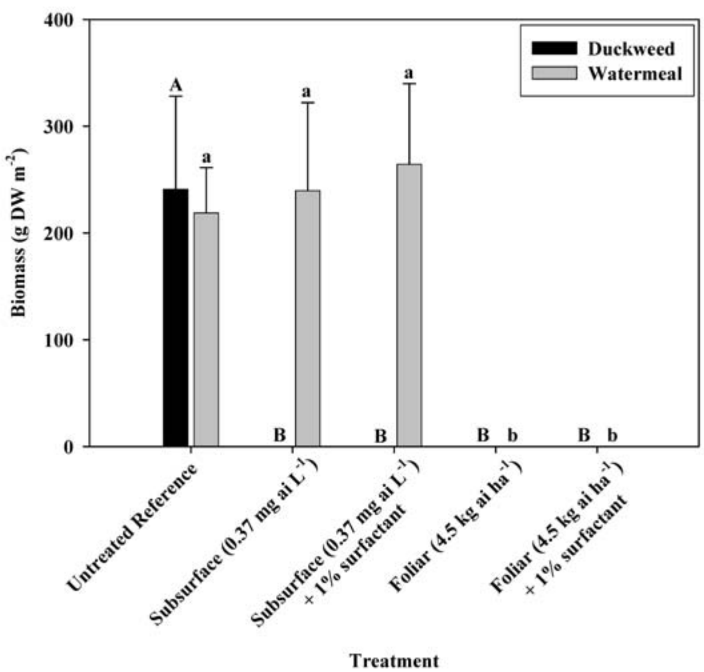

Figure 1. Mean biomass (±1 SE) of duckweed (*Lemna minor*) and watermeal (*Wolffia* spp.) harvested 28 DAT with foliar and submersed applications of diquat either with or without a methylated seed oil surfactant. Bars sharing the same letter are not statistically different at p = 0.05 according to a Fisher's Protected LSD test. Analyses were conducted within species.

Diquat was reported to be efficacious against watermeal as a subsurface treatment at an aqueous concentration of 0.40 mg ai L^{-1}, where control of 94% was achieved by 21 DAT (Mudge et al. 2007). The efficacy achieved in the study by Mudge and collaborators may be attributed to the smaller amount of plant material used, mat thickness at the time of herbicide treatment, or water quality. The water used in the previous study was tap water from a clean source (Christopher Mudge US Army ERDC, pers. comm.). In our study, the source water was from an irrigation pond that may have had a greater amount of suspended sediment or other organic particles resulting in increased diquat binding and overall degradation of the herbicide. If so, then the concentration of diquat may not have remained high enough in the pond water to control watermeal in this study. Blackburn and Weldon (1965) concluded that a diquat concentration of >0.50 mg ai L^{-1} is required for watermeal control in small ponds. However, this rate exceeds the maximum labeled concentration for diquat and therefore cannot be used as an application recommendation.

Watermeal is typically difficult to control in field situations, as demonstrated in early small pond studies (Blackburn and Weldon 1965). Watermeal species are the smallest flowering plants worldwide at 0.5-2 mm (Crawford and Landolt 1995). Due to their small size, the vasculature structure has been greatly reduced so that watermeal species lack roots, xylem, and phloem tissues (Landolt 1986). Furthermore, Bernard et al. (1990) reported that *Wolffia australiana* (Benth.) den Hartog & van der Plas had a thick cuticle. White and Wise (1998) reported the cuticle of *Wolffia borealis* (Engelmann ex Hegelmaier) Landolt & O. Wildi. to be ≥1 µm thick, and this cuticular layer was similar on aerial and submersed portions of the fronds. The lack of vasculature tissue for herbicide mobility and the presence of a thick cuticle on both the upper and lower portions of the fronds may have limited the movement of diquat across the submersed cuticle, reducing the efficacy of subsurface treatments.

There may also be a greater resiliency toward herbicide applications during the division process of watermeal species (Mudge et al. 2007). Watermeal typically reproduce vegetatively through the production of daughter fronds within a budding cavity on the mother plant. Within this budding cavity, up to two second-generation daughter fronds and a third generation frond in various stages of development have been observed (Bernard et al. 1990). New fronds are produced in the budding cavity behind older fronds (White and Wise 1998). If diquat degradation is rapid within the water column, then contact with developing fronds in the budding cavity may not occur. When released, these fronds mature and produce new plants of their own as young fronds become photosynthetically active early in development (White and Wise 1998). If a subsurface herbicide application is not effective at controlling all individuals, the rapid growth rate of watermeal can re-infest a waterbody within weeks. We achieved 50% control of watermeal by seven DAT in both subsurface application treatments; however, by 21 DAT there was no control. On average, the life span of a watermeal plant is 17 ± 1 days and the average number of fronds produced per plant is 11 ± 1, with an observed maximum of 15 fronds produced per plant (Bernard et al. 1990), resulting in a doubling time of approximately 2 to 3 days. In contrast, duckweed produced 4 to 16 fronds in 36 days (Bernard et al. 1990) resulting in a doubling time of approximately 5 days.

Results from this study show that excellent control of duckweed can be obtained using foliar and subsurface applications of diquat. The use of methylated seed oil did not increase diquat efficacy for either species. Watermeal was less susceptible to diquat using subsurface applications, possibly due to the presence of a submersed cuticle limiting diquat penetration or the rapid growth of surviving plants to recolonize our tanks. However, excellent control of watermeal was achieved using foliar applications. Additional research is needed at the pond scale to further test the results of these small-scale trials. Also, new herbicides available for use in aquatic plant management bring opportunities for more effective control of watermeal with one of these herbicides or a combination of herbicides.

ACKNOWLEDGMENTS

We would like to thank the Aquatic Ecosystem Restoration Foundation for supporting this project, with additional support from Syngenta Professional Products. We thank Joshua Cheshier, Jimmy Peeples, and Matt Gower for their assistance in setting up the study. We thank Victor Maddox, Christopher Mudge, and Linda Nelson for internal reviews of an earlier version of this manuscript. Approved for publication as Journal Article No. J-11379 of the Mississippi Agricultural and Forestry Experiment Station, Mississippi State University. Citation of trade names does not constitute endorsement or approval of the use of such commercial products.

LITERATURE CITED

Analytical Software. 2003. Statistix 8. Analytical Software, Tallahassee, FL.

Bernard, F. A., J. M. Bernard and P. Denny. 1990. Flower structure, anatomy and life history of *Wolffia australiana* (Benth.) den Hartog & van der Plas. Bull. Torrey Bot. Club. 117:18-26.

Blackburn, R. D. and L. W. Weldon. 1965. The sensitivity of duckweeds (Lemnaceae) and azolla to diquat and paraquat. Weeds 13:147-149.

Crawford, D. J. and E. Landolt. 1995. Allozyme divergence among species of *Wolffia* (Lemnaceae). Plant Syst. Evol. 197:59-69.

Davies, P. J. and D. E. Seaman. 1968. Uptake and translocation of diquat in eledea. Weed Sci. 16:293-295.

Hazen, J. L. 2000. Adjuvants terminology, classification, and chemistry. Weed Tech. 14:773-784.

Hillman, W. S. 1961. The Lemnaceae or Duckweeds, pp. 221-287. *In*: E. H. Fulling (ed.). The Botanical Review: Interpreting botanical progress. The New York Botanical Garden.

Ice, J. and R. Couch. 1987. Nutrient absorption by duckweed. J. Aquat. Plant Manage. 25:30-31.

Landolt, E. 1986. The family Lemnacea - a monographic study. Vol 1. Veroff Geobot Inst. ETH. Vol. 71. Stiflung Rubel, Zurich. 566 pp.

Langeland, K. A., O. N. Hill, T. J. Koschnick and W. T. Haller. 2002. Evaluation of a new formulation of Reward Landscape and Aquatic Herbicide for control of duckweed, waterhyacinth, waterlettuce, and hydrilla. J. Aquat. Plant Manage. 40:51-53.

Meijer, L. E. and D. L. Sutton. 1987. Influence of plant position on growth of duckweed. J. Aquat. Plant Manage. 25:28-30.

Mudge, C. R., L. A. Gettys and W. T. Haller. 2007. Activity of four herbicides on watermeal. Aquatics 29(4):4-6.

Parr, L. B., R. G. Perkins and C. F. Mason. 2002. Reduction in photosynthetic efficiency of *Cladophora glomerata*, induced by overlying canopies of *Lemna* spp. Water Res. 36:1735-1742.

Syngenta Corp. 2007. Reward Landscape and Aquatic Herbicide. http://www.syngentaprofessionalproducts.com/labels/Index.asp?nav=PrdLst&F=PrdDsp. Accessed Sept. 2008.

White, S. L. and R. R. Wise. 1998. Anatomy and ultrastructure of *Wolffia columbiana* and *Wolffia borealis*, two nonvascular aquatic angiosperms. Int. J. Plant Sci. 159:297-304.