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Investigating Minimum Exposure Time Requirements of Diquat for Flowering Rush (*Butomus umbellatus*) Control

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PURPOSE: The purpose of this study was to investigate the minimum exposure time requirements for submersed treatments of diquat to effectively control flowering rush (*Butomus umbellatus* L.). Identifying these parameters will provide critical information for the operational management of this species in high water exchange scenarios.

BACKGROUND: The perennial monocot, flowering rush (*Butomus umbellatus* L.), possesses a dynamic ability to establish and thrive in littoral zones of quiescent and flowing water systems. It can grow as an emergent plant along shorelines and/or as a submersed plant in deeper water (up to 6 m) (Countryman 1970; Hroudova et al. 1996; Madsen et al. 2016a). Once established, flowering rush can form monotypic stands that crowd out desirable native vegetation, limit recreational water use, reduce water flow, and impact native fish species (Boutwell 1990; Parkinson et al. 2010). To reduce these negative impacts, effective chemical control strategies are needed.

Diquat (6,7-dihydrodipyrido[1,2-a:2',1'-*c*]pyrazinediium) herbicide has been utilized extensively for the management of aquatic plant species since it was first registered for aquatic use in 1962 (Netherland 2014). It is a fast-acting, broad-spectrum, contact herbicide that works by disrupting photosystem I in susceptible plant species. Symptomology in plant foliage exposed to diquat can occur rapidly (1 to 3 hr) under full sunlight with complete foliar necrosis 24 to 72 hr after treatment (WSSA 2014). In aquatic systems, diquat is an essential tool for free-floating plant control (e.g., duckweed [*Lemna* spp.], watermeal [*Wolfia* spp.], and water lettuce [*Pistia stratiotes* L.]). In addition to diquat's foliar-applied use-patterns, it is also effective when applied subsurface in-water for submersed plant control (e.g., watermilfoils, [*Myriophyllum* spp.], hydrilla [*Hydrilla verticillata* L.f. Royle], etc.). Since diquat is fast-acting and commonly requires shorter exposure times than other registered herbicides, it is often utilized for treatment of small areas or areas subject to rapid water exchange where herbicide exposure time is limited. Diquat efficacy can also be impacted by water column turbidity as the diquat cation is rapidly and irreversibly adsorbed to negatively charged binding sites rendering it biologically unavailable (Weber et al. 1965; Narine and Guy 1982; Poovey and Getsinger 2002; Hofstra et al. 2001; Poovey and Skogerboe 2004).

Small-scale research and field demonstrations have documented success managing flowering rush with submersed treatments of diquat (Poovey et al. 2012, 2013; Madsen et al. 2016b, 2016c; Turnage et al. 2019; Parsons et al. 2019; Sartain et al. 2021). Although it is classified as a contact herbicide and translocation within exposed plant tissue is limited to the apoplast (WSSA 2014); diquat can provide long-term, selective control of flowering rush by reducing vegetative growth and exhausting energy reserves (i.e., roots, rhizomes). Multiple diquat treatments annually in Detroit Lakes, MN, were an effective means of reducing above- and belowground flowering rush biomass as well as rhizome bud density with minimal adverse effects on native plant communities (Madsen et al. 2012, 2013, 2016c; Turnage et al. 2016).

The ability of flowering rush to grow in a variety of habitats and conditions has led to its spread and establishment in hydrodynamic water bodies where high rates of water exchange can occur, which presents unique operational management challenges (Getsinger et al. 1996). Previous research has shown that diquat or products containing diquat can provide effective flowering rush control when exposure time is at least three hours (Sartain et al. 2021). However, submersed herbicide applications in hydrologically complex systems, such as run-of-the river hydroelectric power reservoirs, exposure times greater than three hours are not always feasible. Water levels and reservoir discharge patterns are primarily driven by regional power demands that fluctuate hourly. Limited suitable herbicide options for flowering rush control in complex hydrological systems coupled with previous successes with diquat, led to the following investigation of diquat's minimum exposure time requirements for flowering rush control.

MATERIALS AND METHODS: Studies were conducted at the US Army Engineer Research and Development Center (ERDC) in Vicksburg, MS, to evaluate the minimum exposure time requirements of diquat for controlling flowering rush. Flowering rush rhizome segments (5 to 8 cm in length) collected from culture stocks at ERDC were utilized for planting during both experimental runs (Trial 1 and Trial 2). Planting methods consisted of placing one rhizome segment with at least one attached bud into 946 ml plastic pots filled with topsoil[1] and amended with 1.04 ± 0.05 g of slow-release fertilizer[2]. Each rhizome segment was placed onto the topsoil and capped with a 1 cm layer of masonry sand to prevent suspension of soil and loss of nutrients in the water column. Potted rhizomes were placed in a 378 L tank filled with tap water (15 cm depth) in a greenhouse to initiate sprouting. Approximately two weeks after planting (WAP), all potted rhizomes had produced healthy green shoots 20 to 40 cm in length. Plants were then relocated to controlled temperature (25 ± 1°C) and light (14:10 light versus dark) environmental growth chamber. Two pots each were placed into 55 L aquaria filled with reverse osmosis (RO) water amended with Smart and Barko nutrient solution (Smart and Barko 1985). Trial 1 plants were acclimated to chamber conditions for approximately two weeks (approximately four weeks since sprouting) and Trial 2 plants were acclimated for five weeks (approximately seven weeks since sprouting).

Experiments were set up as a completely randomized design. Each aquaria, containing two pots, were randomly assigned to one of two diquat[3] treatment rates (370 and 190 $\mu g\ L^{-1}$). Each treatment was administered as an in-water injection and maintained for 15-, 30-, or 60-min exposure times. Each herbicide rate and exposure time combination was replicated during each trial (n = 6). To remove aqueous herbicide residues at the termination of assigned exposure periods, aquaria were drained, refilled twice with RO water, and refilled a third time with the Smart and Barko nutrient solution (Smart and Barko 1985). Water quality parameters for the two trials are shown in Table 1. Final harvest was conducted at four weeks after treatment (WAT) and consisted of removing both pots from each aquaria, harvest of viable shoot and rhizome material, and counting the

[1] Gardenese Topsoil®, Phillips Bark, 428 County Farm Lane, Brookhaven, MS 390601
[2] Osmocote®, The Scotts Company, PO Box 606, Marysville, OH 43040
[3] Reward®, Syngenta Crop Protection LLC. PO Box 18300, Greensboro NC 24719-8300

number of sprouted, developed, and developing buds among both pots. Shoot and rhizome biomass were then sorted, dried at 65°C, and weighed to the nearest 0.01 g. Data were analyzed as gram dry weight (DW^{-1}) biomass per aquaria. Due to varying establishment periods between Trial 1 and Trial 2, data for each trial were analyzed separately. Data were subject to a one-way analysis of variance (ANOVA) in SAS® version 9.4 (2016) using a generalized linear model to test for significant treatment effects. Mean comparisons were performed using a Tukey's Studentized Range Test at $\alpha = 0.05$.

Table 1. Water quality data recorded just prior to treatment of flowering rush with diquat for Trial 1 and Trial 2.

	$H_2$0 Temp. (°C)	Turbidity (FNU)	pH	Cond (µs/cm)	Dissolved O^2 (mg L)
Trial 1	24.71 ± 0.45	0.38 ± 0.28	7.61 ± 0.04	291 ± 24.63	7.96 ± 0.09
Trial 2	24.39 ± 0.04	-0.22 ± 0.06	9.17 ± 0.03	254 ± 2.64	8.31 ± 0.01

RESULTS AND DISCUSSION: When compared to control plants at 4 WAT, diquat treatments reduced shoot and rhizome biomass, 88% and 67% and 91% and 49% in Trial 1 and 2, respectively (Figure 1). Herbicide injury to flowering rush shoots was apparent five to seven days after treatment (DAT). Symptoms consisted of necrotic plant shoots and shoot detachment from the plant base. Visual observations of flowering rush shoots throughout the duration of both trials did not indicate differences among diquat treatments, in that the 190 µg L^{-1} rate 15-min exposure time performed similarly as the 370 µg L^{-1} rate 60-min exposure time. The number of developing, developed, and sprouted rhizome buds were also less in treated plants than control plants apart from the 190 µg L^{-1} rate 15-min exposure treatment in Trial 2.

Although biomass reductions were observed in both trials, no treatment resulted in plant death. New shoot growth was documented at 20 and 12 DAT for Trial 1 and 2, respectively. New growth of Trial 2 plants was more pronounced than Trial 1 plants; likely due to increased rhizome biomass and number of buds from an extended growing period prior to treatment. These results agree with previously conducted small-scale studies investigating submersed applications of contact herbicides for flowering rush management. Madsen et al. (2016a) and Turnage et al. (2019) reported single diquat applications reduced above- and belowground biomass at eight and 52 WAT, respectively. Sartain et al. (2021) reported similar results where diquat or products containing diquat, albeit at longer exposure times, provided ≥ 95% and 64% control of flowering rush shoot and rhizome biomass 4 WAT.

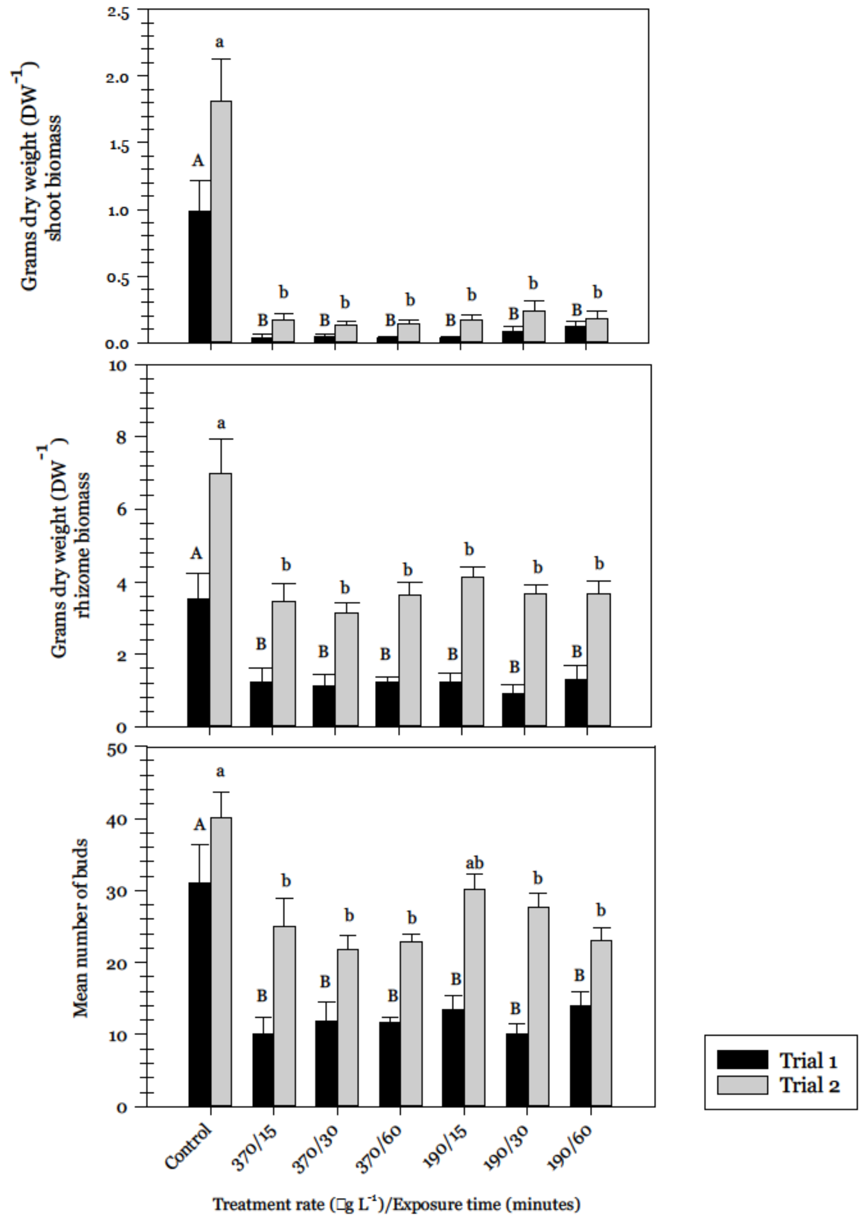

Figure 1. Flowering rush shoot biomass (*top*), rhizome biomass (*middle*), and mean number of buds (*bottom*) in response to diquat applied at a 370 and 190 µg L^{-1} rate under 15-, 30-, and 60 min exposure times. Biomass is expressed as mean grams dry weight (±SE) and bud number as mean number of buds per aquaria (mean ± SE). Different upper case (Trial 1) and lower case (Trial 2) letters indicate significant difference among treatments (α = 0.05).

In addition to flowering rush, diquat can provide control of Eurasian watermilfoil (*Myriophyllum spicatum* L.), sago pondweed (*Stuckenia pectinate* L.), American pondweed (*Potamogeton nodusus* Poiret), and egeria (*Egeria densa* Planchon) under simulated flowing water conditions with estimated diquat half-lives ≥2.5 hr (Skogerboe et al. 2006). The research by Skogerboe et al.

(2006) also indicated that diquat susceptibility is species specific as the submersed plants hydrilla and egeria differed in their response to diquat even though they are close taxonomic relatives.

The result of this study indicates that flowering rush is susceptible to diquat when exposure times are ≥15 min. Flowering rush has and is expanding to complex hydrodynamic systems; however, its high susceptibility to diquat at such short exposure times further supports diquat use for management. Given the propensity of diquat to rapidly bind to suspended sediments in the water column it is plausible that diquat efficacy on flowering rush in an operational setting is more limited by water turbidity as opposed to duration of exposure. Future research should evaluate alternative application techniques such as drip or metered treatments and expand on the work by (Poovey and Getsinger 2002) on the relationship between water turbidity and diquat efficacy for managing flowering rush.

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