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Evaluation of aquatic herbicides applied under simulated drawdown conditions for control of dioecious hydrilla subterranean turions

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ABSTRACT

The use of drawdowns for aquatic weed control has been practiced for many years across the United States. However, highly persistent aquatic weeds such as hydrilla are not thoroughly controlled from drawdown conditions because of the production of desiccation-tolerant propagules like turions. Therefore, an experiment was conducted in Florida to evaluate hydrilla suppression following herbicide treatments during simulated drawdown conditions. Herbicide treatments included the 0.5, 1, and 2× foliar or drawdown rates of bispyribac-sodium, imazamox, penoxsulam, flumioxazin, topramezone, and florpyrauxifen-benzyl. Treatments were made to dishpans planted with hydrilla subterranean turions and transferred to a pond 7 d after treatment (DAT). Bispyribac-sodium and imazamox provided 95 to 100% control in both experimental runs across all rates. Penoxsulam, topramezone, and florpyrauxifen-benzyl did not perform consistently in both experimental runs; however, all provided excellent hydrilla biomass suppression in one of two site-years. Flumioxazin performed consistently across both experimental runs resulting in 70 to 89% biomass reduction. These results indicate high potential utility of currently registered aquatic herbicides for hydrilla control when applied under drawdown conditions.

Key words: chemical control, dewatered, growth retardant

INTRODUCTION

Substantial seasonal variations in water levels can drive shifts in aquatic plant community abundance and composition, population dynamics of sport fish, and nutrient levels (Chow-Fraser et al. 1998, Havens et al. 2004, 2005, Van Geest et al. 2005, Sharip et al. 2012). However, many systems in the United States today are stabilized by water control structures for flood control and water supply (Arnold 1988). The use of drawdowns is a widely accepted tool for both fisheries and aquatic plant management and has been practiced since the 1940s in systems where it is feasible (Hinman and Hess 1949, Heman et al. 1969, Richardson 1975, Cooke 1980, Nagid et al. 2015). Drawdowns in the United States are most common during fall and winter months (Cooke 1980). Aquatic plant control from drawdowns is achieved primarily through desiccation in southern states; whereas in the northern United States, greater aquatic plant control from drawdowns has been attributed to the combined effects of desiccation and freezing temperatures (Richardson 1975, Reimer 1984, Wersal et al. 2013, Bellaud 2021), though insulation by snow cover in northern states may provide propagule protection from freezing temperatures.

The efficacy of drawdowns on aquatic plants is species-specific (Cooke 1980). Submersed plants that primarily reproduce from root crowns and vegetative fragments (e.g., *Myriophyllum* spp., *Cabomba* spp., *Ceratophyllum* spp., and *Egeria* spp.) are typically more susceptible to drawdowns (Cooke 1980, Bellaud 2021). For example, egeria (*Egeria densa* Planch.) and cabomba (*Cabomba caroliniana* A. Gray var pulcherrima Harper) were effectively controlled for a full growing season following a 4-mo drawdown during fall and winter months in Louisiana (Manning and Johnson 1975). In addition, greater weed control following drawdowns has been suggested to occur when higher turbidity, water levels, and lower temperatures occur during spring refill periods (Manning and Sanders 1975). Species that produce abundant seeds, turions, or winter buds such as hydrilla [*Hydrilla verticillata* (L.f.) Royle], naiads (*Najas* spp.), and pondweeds (*Potamogeton* spp.) are generally not controlled by drawdowns and often increase in coverage and density following refill due to reduced competition from slower colonizing species (Kadlec 1962, Nichols 1975, Cooke 1980, Poovey and Kay 1998). Two growing seasons after a 3-mo drawdown at Lake Ocklawaha, Florida, hydrilla had increased from 10 ha (pre-drawdown) to more than 650 ha (Hestand and Carter 1974, 1975). Drawdown effects are very brief for hydrilla in particular because of its persistent subterranean turions that commonly found at densities as high as 1,000 turions m^{-2} (Haller and Sutton 1975, Harlan et al. 1985, Sutton and Portier 1985, Van and Steward 1990). Following a 12-mo drawdown of Lake Ray Roberts in Texas, no reductions in hydrilla subterranean turions or viability were observed (Doyle and Smart 2001). Furthermore, hydrilla subterranean turions consist of 50 to 60% water by weight and will maintain viability unless water content is reduced to 10% (Doyle and Smart 2001).

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A potential management technique to improve the efficacy of drawdowns on troublesome submersed aquatic species such as hydrilla is to integrate herbicide application during dewatered periods. This technique is practiced in some areas of the United States but is not well represented in the scientific literature. Manning and Johnson (1975) reported hydrilla recruitment from turions following dewatered treatments of 2,4-D amine at 6 kg ha^{-1}. Steward (1980) evaluated several herbicides and growth regulators on hydrilla subterranean turions and discovered that only fenac (2,3,6-trichlorophenyl acetic acid) and dichlobenil (2,6-dichlorobenzonitrile) suppressed hydrilla regrowth from these structures in laboratory and pond studies. Fenac, dichlobenil, and silvex [2-(2,4,5-trichlorophenoxy)-propionic acid] were also reported to control *Potamogeton* species in western irrigation canals (Frank et al. 1963). However, fenac, dichlobenil, and silvex were not reregistered for aquatic use in the late 1970s and early 1980s. Published studies on drawdown applications of currently registered aquatic herbicides is limited to sago pondweed (*Stuckenia pectinata*) and flowering rush (*Butomus umbellatus*). Vassios (2010) reported 74 to 77% biomass reduction 30 d after treatment of sago pondweed tubers in drawdown applications of imazamox, imazapyr, penoxsulam, fluridone, or flumioxazin. Likewise, drawdown applications of imazapyr and imazamox reduced flowering rush in Idaho (Getsinger and Madsen 2021). Since drawdowns alone provide only short-term control of hydrilla, and no published data exist in the literature on the efficacy of currently registered aquatic herbicides, the objective of this work was to evaluate currently registered aquatic herbicides for hydrilla control when applied under drawdown conditions. If hydrilla growth can be retarded and the longevity of control from a drawdown can be extended by a dewatered herbicide application, this practice could become a practical management option where possible.

MATERIALS AND METHODS

An experiment was conducted from winter to spring of 2020 (initiated in January) and repeated in 2022 (initiated in February) to evaluate the use of aquatic herbicides applied in a simulated drawdown to determine their impacts on hydrilla growth from subterranean turions. The experiment was set up as a completely randomized design with four replications and a factorial arrangement of treatments plus a nontreated control. Factors consisted of herbicide (bispyribac-sodium[1], imazamox[2], penoxsulam[3], flumioxazin[4], topramezone[5], and florpyrauxifen-benzyl[6]) and rate (0.5×, 1×, or 2× the maximum foliar or dewatered use rate) (Table 1). In the second experimental run, three additional herbicide active ingredients were included and replicated at single (1×) use rates: potassium salt of endothall[7], dichlobenil[8], and imazapir[9]. Potassium salt of endothall was included because, to our knowledge, this formulation had never been evaluated under drawdown conditions. A use rate of 7.1 kg ai ha^{-1}was used based on a previous Florida 24C label for foliar applications to control floating plants (G. Adrian, pers. comm.). Imazapyr was included because it has a 24C label for drawdown use in Florida as well as recently reported efficacy on flowering rush (*Butomus umbellatus* L.) when applied during drawdown conditions in Montana (Getsinger and Madsen 2021). Lastly, dichlobenil was included as a historical reference treatment based on its previous aquatic registration and high levels of efficacy on hydrilla (Taylor 1966, 1967, Steward 1980).

Table 1. Hydrilla biomass reduction following simulated drawdown herbicide treatments.

Herbicide	Rate (g ai ha^{-1})	% Biomass reduction[1,2] 2020	2022
Bispyribac-sodium	56	99 a	95 ab
	112	100 a	95 ab
	224	100 a	95 ab
Imazamox	561	96 ab	96 ab
	1,123	100 a	96 ab
	2,245	99 a	96 ab
Penoxsulam	98	94 ab	41 f
	197	95 ab	43 f
	393	99 a	44 f
Flumioxazin	211	71 c	74 de
	422	70 c	79 cd
	844	81 bc	89 abc
Topramezone	195	7 f*	61 e
	390	10 f*	76 cd
	779	31 e	94 ab
Florpyrauxifen-benzyl	29	7 f*	93 ab
	58	53 d	94 ab
	117	87 ab	100 a

[1]Means followed by the same letter are not different according to Fisher's LSD test ($\alpha = 0.05$).
[2]Asterisk signifies mean is not significantly different from the nontreated control (biomass of nontreated controls was 376 g dishpan^{-1} in 2021 and 431 g dishpan^{-1} in 2022).

Plastic dishpans[10] (11.4 L; 34 cm long, 29 cm wide, and 14 cm deep) were filled with 10.5 cm of masonry sand (no organic matter; pH 7.5 to 8.5) amended with slow-release fertilizer (8-6-12, Osmocote Classic)[11] at a rate of 1.5 g kg^{-1} of dry sand. Masonry sand was used to provide the best-case scenario for herbicide availability to subterranean turions by minimizing soil sorption. Drain holes (7 mm) were drilled in each bottom corner of the dish pans for excess water to drain during incorporation and to fill from the bottom with water in the grow out pond during refill. Dishpans were then placed on ground cloth in an unheated greenhouse in Gainesville, FL. Fluridone-susceptible dioecious hydrilla subterranean turions were collected and screened for maturity from the sediments of a shallow pond at the University of Florida (29°43′17.55″N; 82°25′2.28″W). After quiescent subterranean turions were collected, they were placed in a sealed plastic bag to minimize exposure to atmospheric oxygen and kept in the dark at room temperature overnight prior to planting. The purpose of this special handling was to keep the subterranean turions from breaking dormancy and sprouting before being placed in the experimental grow out ponds (Netherland 1997).

Approximately 18 h after subterranean turion collection, dish pans were watered with 13 mm of simulated rainfall, and 20 subterranean turions per dishpan were evenly placed on the surface of the sand, then covered with an additional 2.5 cm of moist sand. Dishpans were then treated with the herbicide treatments and randomly placed back in the greenhouse. In 2022, three additional herbicides at a single maximum rate were included for reference. Herbicides were applied with a handheld boom equipped with XR11005 nozzles[12] and a CO_2-pressurized backpack sprayer calibrated to deliver 934 L ha^{-1}at 276 kPA. Following application, 13 mm of overhead irrigation was applied to all dishpans. Dishpans were left in the greenhouse and received irrigation as needed to keep subterranean turions moist until placement in South Florida Water Management District research ponds (0.3 ha; average water pH ~7) near Wellington, FL, 7 d after treatment (26°37′27.81″N; 80°25′33.06″W) (Guardo et al. 1995). In 2020 dishpans received an additional 13 mm of irrigation at 3 d after treatment (DAT); however, in 2022 dishpans were irrigated with 13 mm at 3 and 6 DAT. Average daily temperatures during greenhouse periods were 9.6 C (SD = 3.2) and 18.0 C (SD = 3.4) in 2020 and 2022, respectively.

Seven days after herbicide application, dishpans pans were randomly placed on ground cloth approximately 40 to 50 cm apart on the bottom of the dry pond. In-flow water pumps were then turned on (18.2 L s^{-1}) to slowly fill the pond (dishpans were submersed in approximately 3 h) and provide a continuous hydraulic retention time of approximately 48 h. The pond was maintained at a water depth of 1.4 m with continuous water flow. After 18 (run 1) and 16 (run 2) wk, all dishpans were collected and hydrilla biomass harvested, rinsed, placed in mesh laundry bags, and dried in a forced air dryer at 60 C for 5 d and weighed (Figure 1).

A separate reference sprouting experiment was set up to determine the percentage viability of collected subterranean turions used in pond experiment. In runs 1 and 2, 160 and 40 mature subterranean turions, respectively, were randomly collected from batches used to plant dishpans. Subterranean turions were then placed in 500 ml beakers (20 turions per beaker) containing 350 ml of water. Beakers were placed on a laboratory bench at room temperature and ambient fluorescent lighting and monitored for 4 wk. Sprouted tubers were counted and removed and water was changed one to two times per week.

Hydrilla biomass data were normalized to the nontreated control and arcsine square-root transformed to improve heterogeneity of variance; however, back-transformed means are presented for clarity. Data were subject to ANOVA to test for main effects and interactions in R (version 3.6.1; R Core Team 2019). Where significant effects were detected, means were separated using Fisher's LSD test (0.05) under the "agricolae" package in R (Mendiburu 2019).

RESULTS AND DISCUSSION

Cumulative subterranean turion sprouting rates in the reference sprouting experiment were ≥80% over the 4-wk period. Additionally, dry aboveground biomass from nontreated controls in the field experiment resulted in 376 and 431 g dishpan^{-1}in 2020 and 2022, respectively, which indicated excellent growing conditions during the experiment (Table 1). A significant interaction between main effects and experimental run were detected; therefore, experimental runs were analyzed separately (Table 1). Likewise, there was a significant interaction between main effects (herbicide and rate) in both years.

Figure 1. Run 1 (2020) dishpans 7 wk after treatment.

Bispyribac-sodium and imazamox performed similarly and reduced hydrilla biomass 95 to 100% across all rates and in both experimental runs (Table 1). These two herbicides were the only products tested that provided > 95% biomass reduction consistently across both years. The primary mechanism for both bispyribac-sodium and imazamox degradation in soil and water is microbial degradation (Aichele and Penner 2005, Kalsi and Kaur 2019). Half-lives ranging from 4 to 41 d have been reported for bispyribac-sodium in terrestrial soils depending on soil pH, organic matter, temperature, and moisture (Chirukuri and Atmakuru 2015, Kalsi and Kaur 2019). Likewise, imazamox has been shown to have a similar soil persistence to bispyribac-sodium in terrestrial soils, especially under low moisture and low pH conditions (Cobucci et al. 1998, Bresnahan et al. 2002, Aichele and Penner 2005). These characteristics in combination with both herbicides' ability to be absorbed by belowground plant tissues have been documented in terrestrial systems to provide varying levels of pre-emergence weed control and carryover injury to subsequent crops (Cobucci et al. 1998, Ball et al. 2003, Pannacci et al. 2006, Teuton et al. 2007, Rood et al. 2012, Lycan and Hart 2017a, b, Harmanci et al. 2024). However, in the current study soil moisture was not limiting, pH was likely between 7.5 and 8.5, and microbial activity prior to placement in test ponds was likely low. Therefore, imazamox and bispyribac were most likely highly available in the soil with minimal microbial degradation.

Penoxsulam performed very well in 2020 resulting in 94 to 99% biomass reduction across all rates tested (Tabel 1). However, in 2022 hydrilla biomass reduction did not exceed 44% from penoxsulam applied at the 2× rate. Though penoxsulam's terrestrial use patterns are largely for post-emergent weed control in rice systems, residual weed control of up to 3 wk after treatment has been reported (Mann 2015, Turra et al. 2023). In the current study, inconsistent results on hydrilla suppression may be due to slightly lower air temperatures in 2020 (9.6 C) than in 2022 (18.0 C) during the period subterranean turions were exposed to herbicide prior to inundation. Penoxsulam has been shown to have a highly variable half-life in terrestrial soils with reported values ranging from 2 to 30 d depending on soil type (Jabusch and Tjeerdema 2006, Monika et al. 2017, Kaur and Kaur 2018). Kaur and Kaur (2018) reported increased penoxsulam dissipation in terrestrial soils when soil moisture and temperature increased. Thus, warmer pre-inundation temperatures in 2022 coupled with the use of coarse masonry sand may have contributed to faster penoxsulam degradation resulting in shorter exposure times to subterranean turions. Furthermore, penoxsulam degradation is faster under more alkaline conditions, which was likely the case in the current study which utilized sand with pH ranging from 7.5 to 8.5 (Joshi and Srivastava 2019).

Hydrilla biomass reduction from drawdown applications of flumioxazin was relatively consistent between years ranging from 70 to 81% reduction in 2020 and 74 to 89% reduction in 2022 (Table 1). Flumioxazin, which is primarily degraded through pH-mediated hydrolysis, can vary greatly in terms soil persistence with terrestrial soil half-lives reported to 10 to 32 d (Ferrell and Vencill 2003, Alister et al. 2008, Mueller et al. 2014, Eason et al. 2022). However, the consistency of flumioxazin across both experimental runs in the current experiment suggests that pH conditions were similar (soil = 7.5 to 8.5; water = 7) in both years and degradation may have not been affected by temperature. Additionally, flumioxazin's efficacy on hydrilla subterranean turions is reasonable considering its extensive pre-emergent use patterns in terrestrial systems (Askew et al. 2002, Grey et al. 2003, Grichar 2006, Richardson and Zandstra 2006, 2009, Mahoney et al. 2014, Herrmann et al. 2017).

Topramezone did not reduce hydrilla biomass compared to the nontreated control when applied at the 0.5× and 1× rates in 2020 (Table 1). However, a topramezone rate response was observed in 2022, and hydrilla biomass was reduced 61 to 94%. In terrestrial systems, topramezone is primarily utilized for post-emergence weed control but does possess some soil residual activity on sensitive species (Rahman et al. 2015). In terrestrial soils, topramezone bioavailability is lower in sandy soils with lower cation exchange capacities and at higher pH (Ramanathan et al. 2023). Considering the use of masonry sand in the current experiment, soil interactions with topramezone should have been identical in both experimental runs with the exception of an additional irrigation event in 2022. However, topramezone's mechanism of action (inhibition of 4-hydroxyphenylpyruvate dioxygenase) requires treated sensitive plants to be exposed to light for bleaching symptoms to appear (Grossman and Ehrhardt 2007). Thus, delayed hydrilla subterranean turion emergence coupled with minimal root formation for herbicide uptake in 2020 due to cooler temperatures (9.6 C) may be an explanation for the observed inconsistent results.

Hydrilla biomass reductions from drawdown applications of florpyrauxifen-benzyl were inconsistent among experimental runs (Table 1). In 2020 a 2× rate was required to achieve 87% biomass reduction; however, in 2022 biomass reduction was at least 93% at the 0.5× rate. Despite the observed inconsistencies, results from 2022 are encouraging considering that florpyrauxifen-benzyl is primarily utilized as a post-emergent option with minimal pre-emergence activity (Miller and Norsworthy 2018, Wright et al. 2020). A potential explanation for inconsistencies among years may again be due to warmer greenhouse temperatures in 2022 that likely promoted earlier turion sprouting and emergence resulting in a slight increase in time for herbicide uptake and activity prior to inundation in test ponds.

Table 2. Hydrilla biomass reduction following simulated drawdown herbicide treatments in 2022.

Herbicide	Rate ($g\ ai\ ha^{-1}$)	% Biomass reduction[1,2,3] (2022)
Potassium salt of endothall	7,100	44 c
Dichlobenil	11,200	100 a
Imazapyr	1,682	93 ab

[1]Biomass of nontreated control was 431 g $dishpan^{-1}$.
[2]Means followed by the same letter are not different according to Fisher's LSD test ($\alpha = 0.05$).
[3]Asterisk signifies mean is not significantly different from the nontreated control.

Reductions in hydrilla biomass in 2022 from drawdown applications of potassium salt of endothall, dichlobenil, and imazapyr were 44, 100, and 93%, respectively (Table 2). Despite endothall having previous soil-applied terrestrial use patterns (Turgeon et al. 1972a,b), application to aquatic sediments with significant microbial activity for degradation likely limits its effectiveness (Simsiman and Chester 1975, Islam et al. 2018). Likewise, Steward (1969) reported minimal phytotoxicity of the cocoamine salt of endothall on hydrilla turions. However, sand typically has very low microbial activity, which suggests that the lack of hydrilla suppression observed from endothall was not due to limited availability. Dichlobenil resulted in 100% reduction of hydrilla biomass, which speaks to its previous aquatic registration and dewatered use patterns (Table 2; Hiltibran 1966). Dichlobenil was first registered more than 60 yr ago for aquatic use and was not reregistered due to its persistence and very high use rates. Its inclusion in the current study suggests that the methodology is suitable since results were similar to those of Steward (1980) (Montgomery et al. 1972, Clausen et al. 2004). Isoxaben and indaziflam, two newer herbicides that share the same mode of action as dichlobenil (inhibition of cellulose synthesis), may be candidates for future aquatic drawdown evaluation. Despite not being labeled for in-water applications or having significant activity on hydrilla, drawdown application of imazapyr resulted in 93% biomass reduction (Table 2; Nelson et al. 1991, Patten 2003). Among aquatic weed scientists, imazapyr is largely considered inactive on submersed aquatic plants due to its relatively short aqueous half-life (Bajrai et al. 2017, Schreiber et al. 2017, Dugdale et al. 2020). However, the hydrilla subterranean turion response observed in the current experiment is more in accordance with reports of its substantial pre-emergent activity in terrestrial systems (Bovey and Senseman 1998, Harrington et al. 1998, Ulbrich et al. 2005, Douglass et al. 2016, Zaccaro et al. 2018).

Overall, hydrilla biomass reduction levels were greatest and most consistent across years following drawdown treatments of bispyribac-sodium and imazamox. These two herbicides also reduced hydrilla biomass similarly at 0.5× and

1× rates, which gives extraordinary forgiveness to applicators for error that cannot be controlled under field conditions. Additionally, bispyribac-sodium and imazamox in both experimental runs, and florpyrauxifen-benzyl in 2022 provided hydrilla control like that of the historical standard active ingredient, dichlobenil.

One of the most compelling aspects of hydrilla subterranean turion response to herbicides under drawdown conditions is how different it can be from whole-plant response from in-water exposure. For example, the slow-acting herbicides tested require several months of exposure time to provide hydrilla control from in-water application (Shearer and Nelson 2009, Getsinger et al. 2011, Sartain 2014, Wood and Netherland 2019). However, in the current experiment, these slow-acting active ingredients provided exceptional hydrilla control after exposing subterranean turions for only 7 d, although theoretical concentrations in the substrate were much higher than typical in-water use rates. Furthermore, this is only under the assumption that once dishpans were covered with water in ponds 7 d after treatment, herbicide concentrations in soil pore water were rapidly reduced due to the diffusive pressure of the surrounding water column.

Much further research is needed on the utility and operational refinement of drawdown herbicide applications. Additional rate-response experiments are recommended to determine optimal and cost-effective doses to extend hydrilla suppression. Likewise, further investigations of the drivers of herbicide consistency and associated environmental conditions are needed as drawdown herbicide applications can be highly variable (Madsen et al. 2017). Similarly, little to no published data exist on drawdown herbicide application selectivity toward key desirable plant species. Future work will also investigate drawdown herbicide efficacy on hydrilla under operational conditions.

In summary, Steward (1980) reported that underground structures of hydrilla such as subterranean turions, rhizomes, and root crowns are responsible for rapid reinfestation following control measures. Therefore, increased effectiveness of hydrilla control practices is dependent on the ability to reduced regrowth potential of underground structures. Based on the observations in the current experiment, there are several currently registered aquatic herbicides with great potential for hydrilla control from drawdown applications.

SOURCES OF MATERIALS

[1]Tradewind®, Valent U.S.A. Corporation, Walnut Creek, CA 94596.
[2]Clearcast®, SePRO Corporation, Carmel, IN 46032.
[3]Galleon® SC, SePRO Corporation, Carmel, IN 46032.
[4]Clipper® SC, Nufarm Inc., Alsip, IL 60803.
[5]Oasis®, SePRO Corporation, Carmel, IN 46032.
[6]Procellacor® SC, SePRO Corporation, Carmel, IN 46032.
[7]Aquathol® K, UPL NA INC, King of Prussia, PA 19406.
[8]Casoron® 4G, UPL NA INC, King of Prussia, PA 19406.
[9]Habitat®, SePRO Corporation, Carmel, IN 46032.
[10]Rubbermaid® dishpan, Newell Brands, Atlanta, GA 30328.
[11]Osmocote Smart Release 15-9-12®, Scotts, Marysville, OH 43041.
[12]XR 11005 nozzles, TeeJet® Technologies, Springfield, IL 62703.

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