Evaluation of sethoxydim for torpedograss control in aquatic and wetland sites

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ABSTRACT

Invasive grasses constitute one of the most difficult aspects of vegetation management in many aquatic and wetland systems. Current management strategies primarily include the herbicides glyphosate and imazapyr, which are effective, but largely nonselective. Sethoxydim is a selective graminicide that recently received a 24(c) label for invasive grass control in aquatic systems in Florida. Here we report data from four field studies conducted at three locations in South Florida from 2015 to 2017 to evaluate the performance of sethoxydim for torpedograss control. Aerial-, ground-, and airboat-applied studies indicated that sethoxydim controlled torpedograss for varying lengths of time, from approximately 1 to 11 mo depending upon several factors. Sequential sethoxydim applications applied in the late spring just before flooding resulted in greater than 90 and 67% control at 180 and 360 d after treatment (DAT), respectively. However, aerial treatments applied in the fall provided only short-term reductions in torpedograss cover of approximately 70% for 2 mo. Airboat spot treatments applied in the fall resulted in greater than 90% control at 120 DAT but torpedograss recovered the following summer. Treatments of glyphosate + imazapyr generally outperformed sethoxydim across most of the studies. These studies indicate that sethoxydim may be useful for selective torpedograss control. However, it will likely be a more nuanced treatment than glyphosate and imazapyr and retreatment intervals should be further clarified.

Key words: glyphosate, imazapyr, *Panicum repens* L., sequential treatments, sethoxydim.

INTRODUCTION

Invasive grasses are consistently problematic for aquatic and wetland managers. Across the United States, multiple species including torpedograss (*Panicum repens* L.), paragrass [*Urochloa mutica* (Forssk.) T.Q. Nguyen], common reed [*Phragmites australis* (Cav.) Trin. ex Steud.], giant reed (*Arundo donax* L.), and reed canarygrass (*Phalaris arundinacea* L.) often displace native vegetation and form near monotypic stands (Tarver 1979, Maurer et al. 2003, Lambert et al. 2010). This in turn may negatively affect littoral and wetland communities through changes in nutrient cycling, hydrology, biomass accumulation, impeded water flow, and reduced navigability of waterways (Dudley 1998, Meyerson et al. 2000). Torpedograss is especially problematic in Florida, where it infests thousands of hectares of wetlands, reduces wildlife habitat quality, and has been suggested to create poor sport-fishing habitat because of its dense tangled mats (Hanlon and Langeland 2000).

For many years, managers have almost exclusively utilized glyphosate and/or imazapyr to control these invasive grasses (Smith et al. 1993, Hanlon and Langeland 2000). Both herbicides can provide seasonal to long-term control of many aggressive grasses. However, both herbicides are nonselective and may injure or kill nontarget plants, especially when invasive grasses are treated in mixed stands of desirable vegetation. This can result in a successional reset of treated areas, which may then be susceptible to reinvasion by the same or new invasive plants. Selective strategies to preserve native plants is often a critical component of management goals.

For torpedograss and other invasive grasses, the scale of the problem is also vast, from small lakes and retention ponds < 1 ha in size to wetlands and lakes several hundreds or thousands of hectares in size. When herbicides are used, there is often a need for multiple application methods including aerial treatment for large areas, ground-based broadcast treatments along canals and in some seasonally dry wetland and mitigation sites, and handgun spot treatments for airboat and backpack applications.

Sethoxydim is a graminicide, or grass-active herbicide that recently received a 24(c) registration in Florida for aquatic grass control (Anonymous 2017). Historically, sethoxydim has been used for control of many weedy grasses in agronomic and noncrop settings and its selectivity has been well established (Burton et al. 1989, Clay et al. 2006, Kukorelli et al. 2013). Previous mesocosm studies have demonstrated excellent selectivity for many native aquatic plants including key monocots such as broadleaf cattail (*Typha latifolia* L.), pickerelweed (*Pontederia cordata* L.), and California bulrush [*Schoenoplectus californicus* (C.A. Mey.) Palla] (Enloe and Netherland 2017). Additional mesocosm studies have demonstrated that sethoxydim applied at 0.53 kg ha^{-1} reduced torpedograss biomass by 62% (Enloe et al. 2018). This level of control was similar to low rates of glyphosate (0.84 kg ha^{-1}) but less than the typical field rate (3.36 kg ha^{-1}) used for torpedograss control (Enloe et al. 2018).

To address potential lower levels of efficacy, sequential applications of graminicides have been studied as an approach to improve their activity on perennial grasses

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that are difficult to control with single applications. In turf studies, Johnson (1992) found that common bermudagrass cover was significantly reduced with monthly treatments of sethoxydim applied at 0.3 kg ha^{-1} for four consecutive months after two successive years of applications. Taverner et al. (2011) found that three monthly applications of sethoxydim at 0.3 kg ha^{-1} reduced torpedograss cover to 10% at 12 wk after initial treatment (WAIT). This was significantly better than results with a single application. Although sequential graminicide treatments increase application costs and may be impractical on large-scale projects, their value should be assessed in aquatic systems given the common use of repeated treatments for many aquatic plant and algae problems (Grant 1962, Crowell et al. 2006).

Given these issues, our objectives were to 1) evaluate sethoxydim efficacy on torpedograss in a variety of aquatic and wetland conditions; 2) examine sethoxydim performance using multiple application methods including aerial and ground broadcast and airboat spot treatment methods; 3) determine if sequential sethoxydim applications 2 and 4 WAIT can improve long-term control compared with single applications; and 4) compare sethoxydim efficacy with glyphosate and imazapyr. Here we report on the first aquatic field studies of sethoxydim for control of torpedograss in the United States.

MATERIALS AND METHODS

Four field studies were conducted at three sites in South Florida during the period of 2015 to 2017. All sites were naturally infested with dense stands of torpedograss that were well established. Not all studies were fully repeated in space or time. However, almost all herbicide treatments were tested in at least two studies. Site conditions and experimental approaches varied by location and are described herein.

Lakeside Ranch Stormwater Treatment Area (STA)

In August 2015, a preliminary field study was initiated at Lakeside Ranch STA (27°9′10.72″N; 80°40′22.75″W) on the northeast side of Lake Okeechobee near Okeechobee, FL. This STA was originally designed for emergent vegetation and was composed of mixed stands of common cattail [*Typha latifolia* (L.)], southern cattail (*T. domingensis* Pers.), knotweed (*Polygonum* spp.), bur-marigold [*Bidens laevis* (L.) Britton, Sterns & Poggenb.], American cupscale [*Sacciolepis striata* (L.) Nash], watersprite [*Ceratopteris thalictroides* (L.) Brongn.], climbing hempvine [*Mikania scandens* (L.) Willd], pickerelweed (*Pontedaria cordata* L.), and other emergent plants. However, in recent years, torpedograss invaded and now occupies many acres of the STA in mixed vegetation stands. Water depth in the STA was maintained at approximately 45 cm, but some fluctuation occurred during the course of the study.

Twenty-four plots, each 0.21 ha in size (46 by 46 m), were established in cell one of the STA and plot corners were marked with permanent polyvinyl chloride (PVC) pipes 2 m in height. Treatments were assigned to each plot in a completely randomized fashion. Treatments included sethoxydim[1] at the maximum labeled broadcast rate (0.53 kg ha^{-1}) and the maximum spot-treatment concentration (5% v/v, which equated to 4.2 kg ha^{-1}), glyphosate[2] (3.36 kg ae ha^{-1}), imazapyr[3] (0.56 kg ha^{-1}), and a nontreated control. All herbicide treatments included a drift control agent[4] at 2.3 L ha^{-1}. Both sethoxydim treatments included methylated seed oil[5] at 1% v/v and the glyphosate and imazapyr treatments included a nonionic surfactant[6] at 0.25% v/v. The number of replicate plots varied by treatment, with three replicate plots each for the nontreated control and sethoxydim (4.2 kg ha^{-1}) treatments and six replicate plots each for the remaining three treatments.

Herbicide treatments were applied on 4 and 5 August 2015. Treatments were applied to each plot from an airboat with a handgun spray applicator at 468 L ha^{-1}. The entire plot was treated by making successive passes with the airboat across the plot. This application method inadvertently resulted in the creation of airboat trails, where subsequent torpedograss control was poor compared with the rest of the plot. These trails were excluded from posttreatment vegetation sampling.

Baseline data were collected 1–4 August 2015, just before treatment and included a visual estimate of torpedograss vegetative cover. Torpedograss cover was estimated in five randomly placed 1-m^2 quadrats along one transect through each plot. Plots were resampled in a random manner at 36, 80, and 164 d after treatment (DAT).

Bonita Springs

A study was conducted April 2016 to June 2017 at the Billy Don Grant Parcel (26°20′10.62″N; 81°40′41.09″W), near Bonita Springs, FL. The site was a constructed wetland mitigation site that was seasonally dry in the winter and had a maximum water depth of approximately 75 cm during the summer wet season. The site was a near-monotypic stand of torpedograss with few other plant species growing in the study area.

Forty plots, 6 by 10 m in size, were established in April 2016 in a randomized complete block design with four replicate plots per treatment. Two experimental runs were initiated. The first was on 28 April 2016 and the second on 28 May 2016. For the first experimental run, the initial treatment was applied on 28 April, the sequential sethoxydim treatment was applied on 13 May 15 d after initial treatment (DAIT), and the repeated sequential sethoxydim treatment was applied on 28 May 2016 (30 DAIT). For the second experimental run, the initial treatment was applied on 28 May, the sequential sethoxydim treatment was applied on 12 June (15 DAIT), and the repeated sequential sethoxydim treatment was applied on 27 June 2016 (30 DAIT). For each application timing, treatments were applied with a CO_2-pressurized backpack sprayer equipped with a 3-m boom at an application volume of 178 L ha^{-1}.

Treatments included a nontreated control, glyphosate + imazapyr (3.36 kg ha^{-1} + 0.56 kg ha^{-1}), and sethoxydim (0.53 kg ha^{-1}), which was applied as a single, sequential, or repeated sequential treatment. For the sequential and repeated sequential treatments, this resulted in total rates of sethoxydim of 1.1 and 1.6 kg ha^{-1}, respectively. A methylated seed oil was added to all herbicide treatments at 2.3 L ha^{-1}. For experimental run 1, pretreatment torpedograss cover was largely comprised of overwintering elevated stems with limited leaf area above a mat of dried thatch and periphyton. All three applications were made before summer inundation. For experimental run 2, torpedograss had initiated new growth and the final treatment was made to new growth 5 to 10 cm above the water at the beginning of summer inundation. For all sequential and repeated sequential treatments, torpedograss was still green to yellow in color and had not desiccated as a result of the initial treatment.

Posttreatment data collection included visual estimates of percent control for each plot, where 0 equals no control and 100 equals complete control (no green torpedograss remaining). Percent control data was collected at 60 and 90 DAIT for each experimental run. However, at 90 DAIT, it became clear that for experimental run 1, all sethoxydim treatments had generally failed, as all plots were less than 68% control, as estimated visually. This resulted in the termination of run 1, but run 2 was continued with percent torpedograss cover data collected at 180 and 360 DAIT. Additionally, in run 2, torpedograss belowground biomass was sampled at 90, 180, and 360 DAIT. Sampling was done with a 15-cm-diam stainless steel aquatic sediment sampler to a depth of 30 cm. This depth resulted in sampling the entire rhizome layer but did not encompass the entire depth of torpedograss roots, which appeared to go much deeper than 30 cm. At each sample date, 10 subsamples were randomly collected from each plot, washed clean of soil and dead material, and pooled into one composite sample per plot. These were then oven dried at 65 C for 72 h and weighed.

Additional rhizomes were collected from each treated plot and transported to a greenhouse at the Center for Aquatic and Invasive Plants in Gainesville, FL. Ten white, firm rhizome pieces, each approximately 10 cm in length, were selected from bulk samples from each plot, washed, and placed in 3-L tubs filled with clean water. At 30 d after removal, all new shoots from each rhizome piece were recorded. There was insufficient rhizome material found in any glyphosate + imazapyr-treated plot and this treatment was not included in the subsequent analysis of sprouting.

C-139 Annex

Two studies were conducted at C-139 Annex, a South Florida Water Management District property slated for restoration. Plots were located within a 324-ha impoundment on the southwest side of the property identified as Pond 3 (26°21′41.57″N; 80°58′14.61″W). Pond 3 was a historically wet prairie that was levied and used for water storage for surrounding orange groves. Water depth is now strongly seasonal and fluctuates from a dry surface in the winter to approximately 60 to 90 cm in the peak of the wet season. Pond 3 is composed of cypress strands mixed with open emergent plant communities dominated by patches of cattail (*Typha* spp.) and extensive monotypic stands of torpedograss and paragrass.

The first study at C-139 Annex was an aerial application study. Twelve plots, ranging in size from 1.3 to 1.6 ha, were established across mixed stands of torpedograss and paragrass. Plots were 27 m in width and 366 to 457 m in length. The 27-m width was designed to accommodate three passes with a helicopter sprayer, boom width 9.1 m, applying at 187 L ha^{-1}. Initial treatments were applied on 4 November 2016 and sequential treatments were applied on 18 November 2016. Treatments included sethoxydim at 0.53 kg ha^{-1} applied as single or sequential applications, glyphosate + imazapyr (4.2 + 1.12 kg ha^{-1}) applied as a single treatment, and a nontreated control. For the sequential sethoxydim treatments, this resulted in a total rate of 1.1 kg ha^{-1}. A methylated seed oil[7] was included in each sethoxydim treatment at 0.94 L ha^{-1} and at 0.24 L ha^{-1} with the glyphosate + imazapyr treatment. Each treatment was assigned to three replicate plots in a completely randomized fashion.

The second study at C-139 Annex was a spot-treatment application study, which was established in a separate part of the impoundment approximately 800 m away. Eight plots, each 11 by 49 m, were placed in an open area of dense, well-established, torpedograss. These plots were treated within a day of each aerial treatment date by airboat with a handgun calibrated to deliver 935 L ha^{-1}. Sethoxydim was applied at 5% v/v, which resulted in 8.4 kg ha^{-1}, applied as single or sequential applications. Glyphosate + imazapyr were applied at 3 and 1%, v/v (4.2 + 1.12 kg ha^{-1}) as a single treatment, and a nontreated control was also included. Treatments were applied by making one pass down the length of each plot edge, spraying into the plot. This allowed spray coverage across the entire width of the plot in two passes and prevented the creation of any airboat trails within the treated area of each plot. A methylated seed oil was included in each sethoxydim treatment at 0.94 L ha^{-1} and at 0.24 L ha^{-1} with the glyphosate + imazapyr treatment. Each treatments was assigned to two replicate plots in a completely randomized fashion.

For both studies, permanent quadrats were randomly placed along a single transect down the length of each plot. Ten quadrats, each 1 m^2 in size, were marked with PVC poles in each aerial-treated plot for a total of 120 quadrats. Five quadrats, each 1 m^2 in size, were marked in each airboat-treated plot for a total of 40 quadrats. In each study, torpedograss cover data was estimated in each quadrat just before treatment (baseline) and at 76, 127, 259, and 334 DAT. These studies were set up in monotypic stands with almost no other emergent species present. Additionally, for both studies, baseline data were collected within each quadrat for water depth and emergent torpedograss height.

Statistical analysis

For the Lakeside Ranch STA study, analysis of variance (ANOVA) was performed as a split-plot mixed model to account for repeated measurements of species cover index using SAS® PROC GLIMMIX (Littell et al. 2006). Herbicide treatment and sampling date (DAT) were considered fixed effects. The main plot error (used to test herbicide treatment) consisted of replication variation among plots after accounting for treatment. The subplot error (used to test sample date and the interaction of sample date with formulation) consisted of replication variation within sample date and treatment. The arcsine transformation was used for the analysis of cover data. The use of this transformation (Snedecor and Cochran 1989) was based on graphical examination of normality and homogeneity of variance. The overall ANOVA was partitioned to perform an overall *F*-test for differences among herbicide treatments for each sample date as well as for differences among sample dates for each herbicide treatment. Mean comparisons were performed using Tukey's adjustment for multiplicity at a 5% level.

For the Bonita Springs studies, the analysis of percent control focused on herbicide treatments applied in programs (single, sequential, or repeated sequential applications). An ANOVA was performed as a mixed model with blocks considered a random effect using PROC GLIMMIX. Herbicide and program were considered fixed effects and DAT considered a repeated measurement on each plot. Covariance for the repeated measures effect (DAT) was modeled using compound symmetry for Run 1 (two evaluation dates of 60 and 90 DAT) and using a Toeplitz structure for Run 2 (30, 60, 90, 180, 360 DAT). The arcsine square-root transformation was required for the analysis of percent control for both studies. The nontreated control was excluded from the ANOVA as percent control values were always 0.

Subsequent analyses on experimental Run 2 were performed as a mixed model with blocks considered random and treatment included as a fixed effect. The analysis of percent cover at 180 and 360 DAT was performed following the methodology for percent control (arcsine square-root transformation, covariance for the 180 and 360 DAT evaluations modeled using compound symmetry). The remaining analyses were performed by DAT. The analysis of sampled rhizome dry weight at 90, 180, and 360 DAT required a log transformation because variation increased with weight. The analysis of the proportion (percentage) of rhizomes sprouting was performed using the binomial distribution and logistic link function options in PROC GLIMMIX. The number of sprouts per rhizome was considered a count and analyzed using the Poisson distribution with an offset calculated as the natural log of the number of rhizomes sampled. The glyphosate + imazapyr treatment was not included in the analysis of rhizome sprouting or number of sprouts per rhizome because rhizomes were lacking for this treatment. Mean comparisons were performed at the 5% level of significance using the Bonferroni–Holm adjustment for multiplicity or Dunnett's adjustment when comparing means with the nontreated control.

For the C-139 aerial and airboat application studies, treatments were applied to plots in a completely randomized design (CRD). For the aerial study, there were six replications of the operational standard and three replications of other treatments. For the airboat application study there were two replications per treatment. For both studies, ANOVA was performed as a CRD with plot variation within treatment considered a random effect (error term for treatment effects) and quadrat measurements considered subsamples. The arcsine square-root transformation was used for percent cover to improve the homogeneity of variance. Treatments were compared in terms of percent cover at each sample date and in terms of initial water depth. The glyphosate + imazapyr treatment was not included in the analysis of percent cover after 0 DAT because torpedograss cover was near 0 with very little variation. Mean comparisons were performed at the 5% level of significance using the Tukey–Kramer adjustment to compare means with each other and Dunnett's adjustment to compare means with the nontreated control.

RESULTS AND DISCUSSION

Lakeside Ranch STA

For torpedograss cover, there was a significant interaction between herbicide treatment and evaluation date ($P < 0.001$). This was driven more by changes in torpedograss cover over time than by herbicide treatment as differences in cover between treatments were found only at a single evaluation date. At 36 DAT, torpedograss cover in the glyphosate, imazapyr, and sethoxydim (4.2 kg ha^{-1}) treatments was 8, 15, and 4%, respectively, and was lower than torpedograss cover in the nontreated control (64%) (Table 1). Torpedograss cover in the sethoxydim (0.53 kg ha^{-1}) treatment was 20% and was not different from any other treatment. There were no differences between any treatments at any other sample date. This was due to a high degree of variation in the plots as torpedograss and other vegetation cover was variable.

When individual herbicide treatments were examined across evaluation dates, cover in the nontreated control did not significantly change over time and ranged from 64 to 53%. Cover in the herbicide-treated plots was initially reduced at 36 DAT and then began to recover at later sample dates, but this varied by treatment (Table 1). For example, cover in glyphosate-treated plots was reduced at 36 and 80 DAT but recovered to pretreatment levels by 164 DAT. In the imazapyr-treated plots, a reduction in cover was observed at 36, 80, and 164 DAT compared with the baseline. For both sethoxydim treatments, cover was lower for all posttreatment evaluation dates compared with the baseline. Additional observations collected at 366 DAT did not indicate any treatment differences as torpedograss had vigorously recovered in all treated plots (data not shown).

Bonita Springs

No sethoxydim treatment in experimental Run 1 provided effective control of torpedograss at either 60 or 90 DAIT. Control averaged 19, 29, and 68% for the single, sequential, or repeated sequential applications, respectively (data not shown). This was in contrast to the glyphosate + imazapyr treatment, which resulted in greater than 97% control over these sample dates (data not shown). Because of the lack of effective control among the sethoxydim treatments, this experimental run of the study was discontinued after the 90 DAIT evaluation. The most likely

Table 1. Torpedograss cover response over time to airboat treatment at Lakeside Ranch Stormwater Treatment Area.

Herbicide	Rate (kg ha^{-1})	% Cover			
		0 DAT[1]	36 DAT	80 DAT	164 DAT
Glyphosate	3.36	65 a[2] X[3]	8 b Z	30 a Y	41 a XY
Imazapyr	0.56	56 a X	15 b Y	13 a Y	23 a Y
Sethoxydim	0.53	61 a X	20 ab Y	23 a Y	30 a Y
Sethoxydim	4.2	74 a X	4 b Z	18 a YZ	18 a YZ
Nontreated	—	58 a X	64 a X	59 a X	53 a X

[1]DAT = days after treatment.
[2]Means followed by the same lowercase letter within a column are not significantly different at the 5% level using Tukey's adjustment.
[3]Means followed by the same uppercase letter within a row are not significantly different at the 5% level using Tukey's adjustment.

explanation for treatment failure is low foliar cover during most of the treatment window for experimental Run 1. This application window occurred near the end of the dry season, where torpedograss cover was low and available leaves were elevated above a dense canopy of dried thatch. Given that sethoxydim has little to no soil activity, the low foliar cover may have precluded adequate absorption and translocation of the herbicide. This is in contrast to the glyphosate + imazapyr treatment, where the soil activity of imazapyr likely overcame the foliar limitation. This is relevant for managers who may need to treat early in the spring, before torpedograss is actively growing. In that case, an imazapyr treatment would be a better alternative than sethoxydim, because of its residual activity.

For experimental Run 2, sequential or repeated sequential sethoxydim applications resulted in significantly better torpedograss control than the single application at all posttreatment evaluation dates except 30 DAIT (Table 2). Two or three sethoxydim applications resulted in greater than 90% control at 90 and 180 DAIT and 67 to 70% control at 360 DAIT. This equated to season-long control with considerable suppression the following spring at 1 yr after treatment. The single sethoxydim application resulted in a maximum of 53% control at 30 DAIT and decreased to 30% control at 360 DAIT. The glyphosate plus imazapyr treatment resulted in excellent control over the entire study and was at 99% at 1 yr after treatment.

Additional cover data collected at 180 and 360 DAIT supported the visual assessment data (Table 3). At 180 DAIT, torpedograss cover was reduced from 78% in the nontreated controls to 45, 6, and 1% in the single, sequential, and repeated sequential sethoxydim applications, respectively. The sequential and repeated sequential sethoxydim treatments were not different from the glyphosate + imazapyr treatment at 180 DAIT. By 360 DAIT, the sequential and repeated sequential sethoxydim applications did not differ and ranged from 21 to 25% cover and were different from glyphosate + imazapyr (3% cover) and the nontreated control (60% cover).

The impact of sethoxydim on torpedograss rhizomes was limited. At 90 and 360 DAIT, no sethoxydim treatment differed in rhizome biomass compared with the nontreated control (Table 3). However, at 180 DAIT, the sequential sethoxydim treatment had lower biomass than the nontreated control but was not different from the other sethoxydim treatments. The glyphosate + imazapyr treatment resulted in almost no sampled rhizome biomass at 90, 180, or 360 DAIT and was different from all other treatments at each sample date.

There were no differences in sprouting from rhizomes collected at 90 and 180 DAIT between any sethoxydim treatment and the nontreated control (data not shown). At 90 DAIT, the percentage of rhizomes producing new shoots ranged from 45 to 56% across treatments and the number of new shoots per rhizome was 2.1 to 3.3. At 180 DAIT, the percentage of rhizomes producing new shoots ranged from 45 to 75% across treatments and the number of new shoots per rhizome was 1.1 to 3.0. This is indicative that there was no inherent suppressive effect of sethoxydim on rhizome sprouting at 90 or 180 DAIT.

C-139 Annex, aerial application

Given the promising results from the Bonita Springs study, we sought to scale up our treatments to evaluate sethoxydim performance with aerial treatment. Pretreatment water depth averaged 50 to 57 cm across plots and was not different between treatments. Similarly, torpedograss above-water shoot height averaged 111 to 125 cm across plots and did not differ between treatments. Given that torpedograss is rooted in the substrate, this represents extremely robust shoot growth (161 to 182 cm) when the underwater shoot height component is included. Pretreatment cover averaged 81 to 91% and was also not different among treatments.

The nontreated control exhibited a typical seasonality in canopy cover, which was high in the fall, declined over the winter into early spring, recovered completely by the beginning of the wet summer season, and remained high into the next fall (Table 4). This pattern was likely a result of a cool, dry period over the winter and spring when

Table 2. Torpedograss control with single or sequential late spring ground-based broadcast applications at Bonita Springs for experimental Run 2.

Herbicide	Rate (kg ha^{-1})	No. of Applications	% Control[2]				
			30 DAIT[1]	60 DAIT	90 DAIT	180 DAIT	360 DAIT
Glyphosate + imazapyr	3.36 + 0.28	1	96 a	99 a	100 a	98 a	99 a
Sethoxydim	0.53	1	53 b	51 b	43 b	29 b	30 c
Sethoxydim	0.53[3]	2	70 ab	95 a	93 a	91 a	67 b
Sethoxydim	0.53[4]	3	65 ab	99 a	99 a	99 a	70 b

[1]DAIT = days after initial treatment.
[2]Mean percent control within columns followed by the same letter are not significantly different at the 5% level using the Bonferroni–Holm adjustment.
[3]The total sethoxydim application rate for the sequential (two) applications was 1.1 kg ha^{-1}. The interval between each application was 15 d.
[4]The total sethoxydim application rate for the repeated sequential (three) applications was 1.6 kg ha^{-1}. The interval between each application was 15 d.

Table 3. Torpedograss cover and rhizome biomass response to single, sequential, and repeated sequential ground-based broadcast applications at Bonita Springs in experimental Run 2.

Herbicide	Rate (kg ha^{-1})	No. of Applications	% 180 DAIT[1]	% 360 DAIT	Rhizome Biomass (g) 90 DAIT	Rhizome Biomass (g) 180 DAIT	Rhizome Biomass (g) 360 DAIT
Glyphosate + imazapyr	3.36 + 0.28	1	0 c[2]*	3 c*	2 b*	0 c*	3 b*
Sethoxydim	0.53	1	45 b*	43 ab	79 a	52 ab	81 a
Sethoxydim	0.53[3]	2	6 c*	25 b*	62 a	11 b*	46 a
Sethoxydim	0.53[4]	3	1 c*	21 b*	90 a	34 ab	64 a
Nontreated	—	—	78 a	60 a	71 a	74 a	66 a

[1]DAIT = days after initial treatment.
[2]Means followed by the same letter within sample days after treatment are not significantly different at the 5% level using the Bonferroni–Holm adjustment. An asterisk denotes that the mean differs from the nontreated control at the 5% level using Dunnett's adjustment.
[3]The total sethoxydim application rate for the sequential (two) applications was 1.1 kg ha^{-1}. The interval between each application was 15 d.
[4]The total sethoxydim application rate for the repeated sequential (three) applications was 1.6 kg ha^{-1}. The interval between each application was 15 d.

conditions are less than optimal for torpedograss growth. Aerial treatments of glyphosate + imazapyr reduced torpedograss cover to near 0 at all posttreatment sample dates (Table 4). Sethoxydim applied at 0.53 kg ha^{-1} reduced torpedograss cover to 34% at 76 DAT, which was lower than the nontreated control. This reduction was characterized by a slow yellowing and subsequent browning of much of the canopy. However, brownout was incomplete and torpedograss initiated new growth by early spring. Subsequent cover evaluations were not different from the nontreated controls at 127 DAT or any later sampling date.

Sequential treatments of sethoxydim resulted in a similar pattern of activity to the single application. Torpedograss cover was reduced to 20% at 76 DAT and was significantly lower than the nontreated control. At 124 DAT, torpedograss cover was 26% but was not different from the nontreated control. Torpedograss continued to recover and was not different from the nontreated control at any later sampling date.

C-139 Annex, high-volume application

For the airboat application study, pretreatment water depths in the plots averaged 36 to 44 cm and were not different among treatments. Pretreatment above-water torpedograss shoot heights averaged 95 to 109 cm and were not different among treatments. Torpedograss pretreatment cover was also high and averaged 79 to 90%, with no differences among treatments.

Torpedograss cover in the nontreated controls exhibited a similar seasonal pattern in cover as in the aerial study. Cover was high in the fall, declined through the winter and early spring, increased by late spring, and remained high through the following fall. Sethoxydim applied as a single spot treatment at a concentration of 8.4 kg ha^{-1} reduced torpedograss cover to 0.1 and 3.1% at 75 and 126 DAT, respectively (Table 5). These were both significantly lower than the nontreated controls at each sample date. However, at 258 and 333 DAT, torpedograss cover increased and was not different from the nontreated control. Sequential spot-treatment applications of sethoxydim at 8.4 kg ha^{-1} initially reduced torpedograss cover in a similar manner to the single spot-treatment application at 76 and 126 DAT. However, longer-term control was not improved with sequential applications compared with the single applications at 258 or 33 DAT. At both later sampling dates, torpedograss control in the sequential plots did not differ from the nontreated controls.

These studies are indicative of several key points regarding sethoxydim use for control of torpedograss in aquatic systems. First and foremost, it is clear that sethoxydim may provide some control or suppression of torpedograss in a variety of aquatic environments. This can be useful, especially in areas of high plant species diversity where selective control or suppression is desired. Selectivity has been previously documented for several key aquatic plant species (Enloe and Netherland 2017) and this is likely the most important aspect of this treatment. Future studies should examine sethoxydim use in areas of mixed stands and after restoration with native species.

Second, in well-established and heavily infested sites, control was often relatively short lived and was not as

Table 4. Torpedograss cover response to single and sequential aerial applications at C-139 Annex.

Herbicide	Rate (kg ha^{-1})	No. of Applications	% Cover[2] 0 DAIT[1]	% Cover 76 DAIT	% Cover 127 DAIT	% Cover 259 DAIT	% Cover 334 DAIT
Glyphosate + imazapyr	4.2 + 0.56	1	88 a[3]	0	0.3	0.4	0.5
Sethoxydim	0.53	1	91 a	34 b*	50 a	76 a	63 a
Sethoxydim	0.53[4]	2	88 a	20 b*	26 a	58 a	56 a
Nontreated	—		81 a	74 a	51 a	81 a	71 a

[1]DAIT = days after initial treatment.
[2]The operational standard was not included in the analysis of percent cover after 0 d after treatment (DAT) because control remained near complete with little variation. Standard errors of quadrat samples for the operational standard were 0.02, 0.25, 0.27, and 0.30% for mean percent cover at 76, 127, 259, and 334 DAT, respectively.
[3]Means followed by the same letter are not significantly different at the 5% level using the Tukey–Kramer adjustment. Means followed by an asterisk are significantly different from the nontreated control using Dunnett's test at the 5% level.
[4]The total sethoxydim application rate for the sequential (two) applications was 1.1 kg ha^{-1}. The interval between each application was 15 d.

Table 5. Torpedograss cover response to single and sequential airboat treatment applications at C-139 Annex.

Herbicide	Rate (kg ha^{-1})	No. of Applications	% Cover[2]				
			0 DAIT[1]	75 DAIT	126 DAIT	258 DAIT	333 DAIT
Glyphosate + imazapyr[3]	3.36 + 1.12	1	83 a	0	0	0	0
Sethoxydim	8.4	1	79 a	0.1 b*	3.1 b*	35 a	55 a
Sethoxydim	8.4[4]	2	90 a	0 b*	0.1 b*	29 a	39 a
Nontreated	—	—	86 a	59 a	31 a	53 a	64 a

[1]DAIT = days after initial treatment.
[2]Treatment means followed by the same letter are not significantly different from each other at the 5% level using the Tukey–Kramer adjustment for multiplicity. Treatment means followed by an asterisk are significantly different from the nontreated control using Dunnett's test at the 5% level.
[3]The operational standard was excluded from the analysis of variance at 75, 126, 258, and 333 d after treatment because torpedograss was not present on any of the 10 sampled quadrats at those evaluations.
[4]The total sethoxydim application rate for the sequential (two) applications was 16.8 kg ha^{-1}.The interval between each application was 15 d.

consistent as tank mixes of glyphosate + imazapyr. Across sites, glyphosate + imazapyr applied by aerial or ground broadcast or by airboat provided excellent torpedograss control at almost all sites for the duration of each study. This difference in performance with sethoxydim may require a re-evaluation of expected management outcomes and an adjustment in typical treatment/retreatment intervals compared with the currently used herbicides. However, for managers unable to use imazapyr, sethoxydim may be a good alternative to glyphosate alone. Glyphosate as a standalone treatment for torpedograss often results in good short-term control but limited to no long-term success (Smith et al. 1993). Given the selectivity of sethoxydim, this may make it a more desirable treatment to protect resident desirable vegetation growing with torpedograss.

Third, sequential sethoxydim treatments did improve control in certain situations. At Bonita Springs, sequential applications of sethoxydim in the late spring resulted in excellent control of torpedograss for several months. However, early spring sequential treatments did not perform as well. Fall sequential aerial broadcast and airboat spot treatments at C-139 Annex also did not improve torpedograss control over single treatments. These differences may be related to the timing or season of application, which is often concomitantly linked to hydrologic conditions. For example, the sequential sethoxydim treatment worked well at Bonita Springs at the end of the dry season. Shortly after the final sequential treatment, water levels rose quickly and remained high over the summer. This is in contrast to C-139 Annex, where water levels were high at the time of treatment and subsided over the winter. The additional water stressor may have helped maintain torpedograss control at the Bonita Springs site. Further evidence to support this lies in the data from rhizome sprouting after removal from the substrate. There was no difference in rhizome sprouting between sethoxydim-treated plots or the nontreated control from sampled rhizomes (data not shown). Additionally, other researchers have found improved paragrass control when burning was done just before flooding, which implicates the suppressive effect of flooding on emergent grass regeneration (Chaudhari et al. 2012). Deeper water has also been shown to reduce torpedograss establishment on Lake Okeechobee (Smith et al. 2004). This is in contrast to an upland turfgrass study where Taverner et al. (2011) found that torpedograss control declined after the termination of repeated applications of sethoxydim. This difference in environmental conditions would indirectly support our arguments of posttreatment inundation as an additional stressor to slow torpedograss recovery. Further studies should be conducted to better quantify this posttreatment inundation effect on control.

Finally, there was some evidence that higher spot-treatment concentrations improved torpedograss control. At C-139 Annex, spot treatments of sethoxydim at 8.4 kg ha^{-1} resulted in 2-mo-longer control than aerial treatments of 0.53 kg ha^{-1}. Although we utilized the maximum spot-treatment concentration allowed by the label (5% v/v), we recognize that this equates to a very limited treated area, given the maximum amount that can be applied in a given application is 0.53 kg ha^{-1}. Additional research should examine lower spot-treatment concentrations at differing retreatment intervals that would equate to typical site-visit intervals already used by aquatic managers.

SOURCES OF MATERIALS

[1]TIGR® herbicide, BASF Corporation, 26 Davis Dr., Research Triangle Park, NC 27709.

[2]Rodeo®, Dow AgroSciences, 9330 Zionsville Rd., Indianapolis, IN 46268.

[3]Habitat®, BASF Corporation, 26 Davis Dr., Research Triangle Park, NC 27709.

[4]Accuracy Polymer, Helena Chemical Company, 225 Schilling Blvd., Collierville, TN 38017.

[5]Dyne-Amic, Helena Chemical Company, 225 Schilling Blvd., Collierville, TN 38017.

[6]Induce NIS, Helena Chemical Company, 225 Schilling Blvd., Collierville, TN 38017.

[7]MSO concentrate, Loveland Products, Inc., Greeley, CO 80632-1286.

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