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Control of delta arrowhead (*Sagittaria platyphylla*) in Australian irrigation channels with long exposure to endothall dipotassium salt during winter

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ABSTRACT

Delta arrowhead [*Sagittaria platyphylla* (Engelm.) J.G. Sm.] is an emergent, aquatic plant, originating from North America, which has invaded aquatic environments in Australia. The plant is particularly problematic in southeast Australia, where it invades earthen irrigation channels and drains. Hydraulic capacity is subsequently reduced, leading to a reduction in the efficiency of water delivery. Options for controlling delta arrowhead in irrigation channels and drains are currently underdeveloped. Previous trials have indicated that a potential control option is to treat irrigation channels that hold standing water during temperate winter conditions with the contact herbicide endothall. This article reports on a field experiment to determine the dose–response relationship for endothall dipotassium salt and delta arrowhead. A 3-wk exposure period of endothall dipotassium salt to delta arrowhead during winter at 5 mg ai L^{-1} provided 69% biomass reduction of the emergent petiolate growth form and 92% biomass reduction of the submersed phyllodial growth form 6 wk after treatment (WAT). Control remained evident at 15 WAT; however, by 26 WAT differences between treatments were not detected. This reduction in biomass confirms endothall dipotassium salt to be a useful tool to reduce delta arrowhead biomass during the spring irrigation period.

Key words: aquatic herbicide, aquatic vegetation, aquatic weed control, chemical control, concentration exposure time, *Sagittaria platyphylla*, water delivery.

INTRODUCTION

Delta arrowhead [*Sagittaria platyphylla* (Engelm.) J.G. Sm.] (also called sagittaria; Alismataceae) is an emergent, aquatic plant, originating from North America, which has subsequently become naturalized in Australia, Indonesia, Panama, South Africa, and the former Soviet Union (Adair et al. 2012). Delta arrowhead is a perennial, monocotyledonous herb, which reproduces by seed (achenes) and vegetatively via stolons and tubers (Jacobs 2011). There are two main leaf forms; the emergent, upright, petiolate leaf form and the submersed, phyllodial leaf form (Haynes and Hellquist 2000). The emergent, petiolate leaf form bears flowers and grows to 150 cm tall and tends to occur in slow-moving water bodies. Leaf size and shape is highly variable and dependent on environmental and management factors. The submersed, phyllodial leaf form produces linear, strap-like leaves and is typically found in deeper water than the emergent, petiolate leaf form. However, phyllodial plants can transform into petiolate plants or remain phyllodial indefinitely, depending on environmental conditions. Delta arrowhead is frost sensitive, but regrowth occurs from submersed or subterranean organs (Adair et al. 2012).

In southeast Australia, delta arrowhead has spread significantly since its introduction in about 1960 becoming a major weed of irrigation and drainage systems (Adair et al. 2012). In 2012, the Australian Government declared the species a Weed of National Significance because of its invasiveness and potential impacts to the economy and environment. An increase in capacity to manage the weed is required because current control methods are underdeveloped (Australian Weeds Committee 2012).

Excessive growth of aquatic plants in earthen irrigation systems reduces their water-carrying capacity, thus compromising the reliability of water delivery to primary producers (Bill 1969, Bakry et al. 1992, Dugdale et al. 2013). Control of delta arrowhead in irrigation channels and drains in Australia relies on foliar applications of herbicide to emergent parts of the plant. The herbicides glyphosate and 2, 4-D are commonly used, and imazapyr, amitrole, and dichlobenil have also been used. High-dose and multiple herbicide applications each year are often required to achieve levels of control in which channel hydraulic capacity is not compromised (Adair et al. 2012).

A potential alternative-control option for delta arrowhead in irrigation channels is to target the submersed parts of the plant. Submersed aquatic weed control with herbicide is dependent on the relationship between herbicide concentration (achieved by dosing the water to a target concentration) and exposure time (Netherland 2009). In Australia, the herbicide acrolein is used for

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controlling submersed aquatic weeds in irrigation channels (Bowmer and Smith 1984) but has been found ineffective on delta arrowhead (M. Finlay, pers. comm.). Diquat is also registered for aquatic use, but it is inactivated rapidly in turbid water (Simsiman et al. 1976), which is common in the irrigation districts of southeast Australia. This results in a short exposure time and, consequently, ineffective control (Bowmer 1982, Hofstra et al. 2001, Clements et al. 2013).

The contact herbicide endothall is widely used to control submersed, aquatic vegetation in the United States (Sprecher et al. 2002). Endothall is effective against a wide range of submersed species (Skogerboe and Getsinger 2001, Skogerboe and Getsinger 2002, Dugdale et al. 2012, Dugdale et al. 2013) and has a low-sorption coefficient (Reinert et al. 1996); thus, it maintains efficacy in turbid water (Hofstra et al. 2001). In the United States, it is used effectively in flowing irrigation channels (Sisneros et al. 1998). Although endothall is usually used on submersed aquatic weeds, the emergent genera burreed (*Sparganium* spp.) is listed on the product label, and recently, endothall has provided control of flowering rush (*Butomus umbellatus* L.), which is a member of the Alismatales order (Poovey et al. 2013).

The primary mode of endothall decay is microbial activity (Reinert et al. 1986). Therefore, we would expect to achieve a longer exposure period during cold water conditions compared with when water temperatures are higher and microbial action is greater. Further, in Victoria (35 to 36°S), Australia, delivery of irrigation water ceases for about six weeks each winter (June to August) and irrigation channels hold standing water (static water conditions). This provides an opportunity for herbicide treatment with longer exposure times to be achieved compared with undertaking control during the irrigation season (Clements et al. 2013). A confounding factor to winter treatments is reduced herbicide efficacy because plants are not actively growing in cold water (Netherland et al. 2000), and plants are large with fibrous stems and crowns.

Effective control ($> 95\%$ biomass reduction) of delta arrowhead has been achieved in field trials in which the slow decay of endothall in static water irrigation channels during winter was exploited. However, only a single concentration and exposure time were used (7 mg ae L^{-1} for > 32 d; Clements et al. 2013). Therefore, to determine how endothall should be used to control delta arrowhead in Australia, we conducted a trial to determine the dose–response relationship when applied to static irrigation channels during southern Australian temperate winter conditions.

MATERIALS AND METHODS

A nonflowing irrigation channel was selected at Cobram East (35°59′42.34″S; 145°45′35.68″E) in northern Victoria, Australia. The linear channel contained abundant delta arrowhead along its length, consisting of both emergent and submersed plants. Using an excavator, earthen bund walls were constructed at intervals along the channel to divide it into 18 separate experimental plots. Plots were, on average, 10 m long by 8 m wide by 0.26 m deep. The experimental design tested five target concentrations of endothall dipotassium salt (0.3, 0.6, 1.2, 2.4, 4.8 mg ai L^{-1}) and an untreated reference, randomized in three replicate blocks of six plots.

Herbicide treatments were applied in mid July 2012 by mixing the required volume of endothall stock solution,[1] based on measured plot volume, in 20 L of water and broadcasting it over each plot. After 3 wk, the herbicide-treated water in each plot was pumped out to a holding channel, and then the bund walls were removed, allowing plots to be refilled with fresh water from the adjacent area of the channel. Plots that contained no herbicide were also pumped out and refilled in the same manner.

Water quality and herbicide concentration

Water samples were taken from each plot before and at intervals after herbicide application to determine endothall concentration and turbidity. An enzyme-linked immunosorbent assay (ELISA)[2] was used to determine endothall concentrations. Turbidity was measured using an instantaneous turbidimeter.[3] Water depth and temperature was logged continuously over the trial period using data loggers.[4]

Efficacy of delta arrowhead control

To determine efficacy of delta arrowhead control, a range of abundance metrics were used before treatment (0 wk after treatment [WAT]) and at 6, 15, and 26 WAT (all posttreatment intervals are measured from the end of the 3-wk exposure period). At 0 and 6 WAT, all above ground delta arrowhead biomass from five preselected quadrats (0.09 m^2) was harvested in each of the 18 plots by pulling out entire plants from within quadrats. Dry-weight biomass of viable aboveground plant material was determined for each plot. For each quadrat in each plot, plants were classified into two growth forms—petiolate or phyllodial—and the five quadrats from each plot were combined. Excess water from each combined sample was removed by spinning in a commercial salad spinner until no droplets were produced, before sample weighing (wet weight), and then subsampling and drying to a constant dry weight (± 0.01 g). The ratio of wet to dry weight for the subsample was then used to calculate total dry weight for each sample. The number of petiolate and phyllodial plants was recorded, along with their basal diameter (at the point of eruption from the sediment). At 15 and 26 WAT, in six selected quadrats per plot, an *in situ* (nondestructive) count was made of the number of emergent leaf blades. To prevent repeated sampling of the same locations at each date, before the trial commenced, the position of all quadrats for each date was selected randomly along three transverse transects.

Statistical analysis

Each measurement was averaged over all quadrats in a plot, and each measurement is presented on a per-square-meter basis. Before statistical analysis of each measurement, for each plot, biomass measurements were logarithmically transformed, and count measurements (plant number and

Table 1. Endothall dipotassium salt herbicide rates applied to delta arrowhead growing in an irrigation channel with static water.[1]

Nominal Target Rate (mg ai L^{-1})	Product Rate[2] (L/ML)	Achieved Rate (mg ai L^{-1})			
		1 DAT	5 DAT	9 DAT	21 DAT
No herbicide	—	ND	ND	ND	ND
0.3	0.59	0.34 (0.06)	0.33 (0.07)	0.31 (0.05)	0.19 (0.08)
0.6	1.18	0.59 (0.14)	0.67 (0.11)	0.54 (0.12)	0.32 (0.05)
1.2	2.37	1.71 (0.70)	1.48 (0.52)	1.28 (0.09)	0.56 (0.40)
2.4	4.73	2.59 (0.24)	2.36 (0.43)	2.59 (0.25)	1.62 (0.24)
4.8	9.47	6.17 (0.60)	5.19 (0.73)	5.15 (0.55)	4.33 (0.70)

ML = megalitre = 1,000,000 L; DAT = days after treatment; ND = not detected

[1] Three replicate plots per treatment. Values in parentheses are 1 SD using between-plot variation.

[2] Endothall dipotassium salt: Cascade, 630 Freedom Business Center Dr., King of Prussia, PA 19406.

emergent leaf-blade number) were square-root transformed. To examine the response of each transformed measurement to achieved endothall rate at 1 d after treatment (DAT) (Table 1), a general linear model was fitted with a term for replicate (three-level factor), and, where appropriate, a covariate was measured at week zero (to account for interplot variability in pretreatment abundance measures), and parsimonious model terms were based on the achieved endothall rate at 1 DAT (Table 2). The parsimonious model terms were chosen to maximize the percentage of variance accounted for by the model, but only if each term was marginally (i.e., after adjusting for all other terms in the model) statistically significant ($P > 0.05$) in the chosen model using a standard analysis of variance F-test. A replicate effect was *a priori* included in each model to account for the randomization restriction imposed by using a randomized block design and also to account for any spatial variation associated with blocking. The covariate was included if the covariate was statistically significant using an *F* test, after adjusting for replicate and achieved endothall rate terms in the model (Table 2). To examine whether there was any information on endothall response from the targeted rate, once the achieved rate was available, an *F* test that compared the general linear model of each measurement with a model that also included the targeted endothall rate as a six-level factor was carried out. All general linear-model analyses used the 18 plots as the unit of analysis.

Response curves and values for each plot are presented after adjusting for replicate and any covariate on the transformed scale used for statistical analysis and then back transforming. All herbicide-rate values presented in Figures 1–3 are the achieved herbicide-rate values for each plot 1 DAT (Table 1).

RESULTS AND DISCUSSION

Water quality and herbicide concentration

Water temperature during the treatment period averaged 8.0 C (SD 1.2; using between-plot variation) within plots and average turbidity measured 198 NTU (SD 47). Average plot depth ranged from 0.22 to 0.31 m at the time of treatment and remained constant for the duration of the 3-wk exposure period.

Endothall concentrations were, on average, 18% (SD 18) above target concentration for each treatment 1 DAT (Table 1). Endothall decay was slow during the exposure period and remained, on average, 36% (SD 17) below target concentrations 3 WAT (Table 1), resulting in a 3-wk exposure period of 5.5 mg ai L^{-1} (SD 1.0) for the three plots targeted at 4.8 mg ai L^{-1}. No herbicide was detected in control plots or in any plots after pumping and refilling.

Endothall decay observed in this trial was slow and consistent with previous studies in cool conditions (Clements et al. 2013). Endothall is often nonpersistent in aquatic environments because of rapid biotransformation and biodegradation by aquatic microorganisms (Sikka and Saxena 1973, Simsiman et al. 1976, Reinert et al. 1986). The extended exposure period achieved in this trial is likely due to the herbicide being applied during cold, winter conditions, when microbial activity is low. We would expect more-rapid decay when conditions are warmer, and similar to previous results documented in the literature, e.g., a half-life of 4 d (Reinert et al. 1985) and to nondetectable concentrations in 1 to 36 DAT (Keckemet 1969, Sikka and

Table 2. Description of general linear models used to describe response of outcome measurements to achieved rate (1 d after treatment) of endothall application.[1]

Measurement	Transformation	Covariate	Achieved Rate Model Terms	P Values*
Week 6				
No. of phyllodial plants	Square root	0 WAT basal diam	Rate	**0.0012**
No. of petiolate plants	Square root	0 WAT basal diam	—	—
Biomass of phyllodial plants	Logarithm	—	Rate	**1.3×10^{-6}**
Biomass of petiolate plants	Logarithm	0 WAT No. of petiolate plants	Log(Rate) if endothall applied and 0 otherwise, Indicator of whether endothall was applied	**8.6×10^{-9}**
Week 15				
No. of emergent leaf blades	Square root	—	Indicator of whether rate > 4	**0.00017**
Week 26				
No. of emergent leaf blades	Square root	—	—	—

WAT = Weeks after treatment

[1] All models include a three-level factor for the design replicates. The *P* value for the achieved rate model is calculated using a variance ratio *F* test to compare the full model of a measurement (including terms for replicate, covariate, and achieved rate) to a similar model without achieved rate terms (including terms for replicate and covariate).

**P* values are bolded when $P < 0.05$.

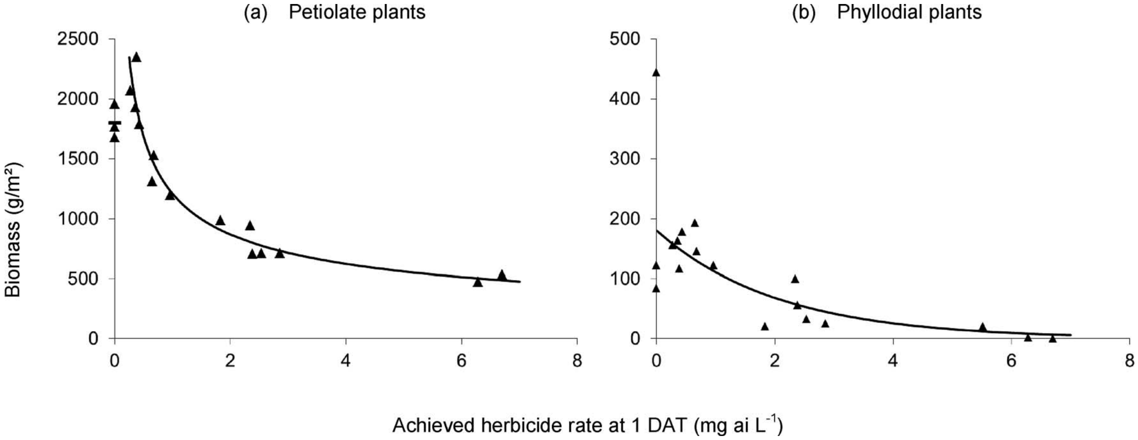

Figure 1. Response of delta arrowhead biomass to endothall rate at 6 wk after treatment (WAT) for emergent (petiolate) and submersed (phyllodial) growth forms. Note different scales on y-axis. The equation for (A) is $\log_{10}(biomass) = 3.25$, when rate = 0, and $\log_{10}(biomass) = 3.08 - 0.478 \times \log_{10}(rate)$, when rate > 0. The equation for (B) is $\log_{10}(biomass) = 2.26 - 0.2109 \times rate$. Each symbol represents one plot. In (A), the dash represents the predicted biomass when no herbicide was applied. Predicted values of petiolate plant biomass at 6 WAT were not available for one plot with a targeted nominal herbicide rate of 4.8 mg ai L^{-1} because the number of petiolate plants at 0 WAT covariate was not measured on this plot.

Rice 1973, Langeland et al. 1986, U.S. Environmental Protection Agency 2005).

Efficacy of delta arrowhead control

Before any chemical application, the population of delta arrowhead within plots was uniformly dense, averaging 269 plants m^{-2} (SD 59) and 2.16 kg m^{-2} (SD 0.52) dry weight (viable, aboveground plant material only). The delta arrowhead population was dominated by the emergent growth form (petiolate plants) averaging 214 plants m^{-2} (SD 59); the number of phyllodial plants averaged 52 plants m^{-2} (SD 19). Average plant basal diameter was 13 mm (SD 5) for petiolate plants and 9 mm (SD 3) for phyllodial plants. Most of the emergent portions of petiolate plants had significant frost damage, but plant material below water was green and healthy.

Endothall rate had a significant ($P \leq 0.0012$) effect on the biomass of both petiolate and phyllodial plants and the number of phyllodial plants at 6 WAT (Table 2). There was no evidence ($P > 0.3$) that the targeted rate had any effect on the response measurements once the effect of achieved rate (1 DAT) was taken into account.

Higher endothall concentrations achieved greater levels of biomass reduction for both petiolate and phyllodial delta arrowhead growth forms (Figure 1). However, for petiolate plants, rates above a minimum threshold (approximately 0.5 mg ai L^{-1}) were required to achieve any biomass reduction (Figure 1). The general linear models predicted that, at 5 mg ai L^{-1} (maximum use rates in the United States; United States Environmental Protection Agency 2005), endothall would provide 69% biomass reduction of the emergent petiolate growth form and 92% biomass reduction of the submersed phyllodial growth form at 6 WAT, relative to untreated delta arrowhead (Figure 1).

There was no effect of herbicide rate on reducing the number of petiolate plants at 6 WAT (Figure 2), indicating that the herbicide destroyed the aboveground portions of

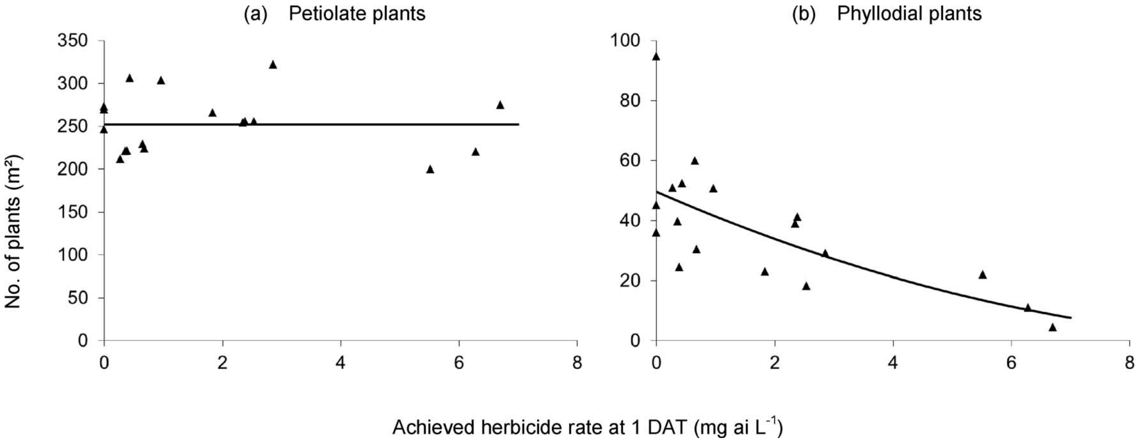

Figure 2. Response of number of delta arrowhead plants to endothall rate at 6 wk after treatment for emergent (petiolate) and submersed (phyllodial) growth forms. Note different scales on y-axis. The equation for (A) is $\sqrt{Number\ of\ \ plants} = 15.88$ at any rate. The equation for (B) is $\sqrt{Number\ of\ \ plants} = 7.04 - 0.611 \times rate$. Each symbol represents one plot.

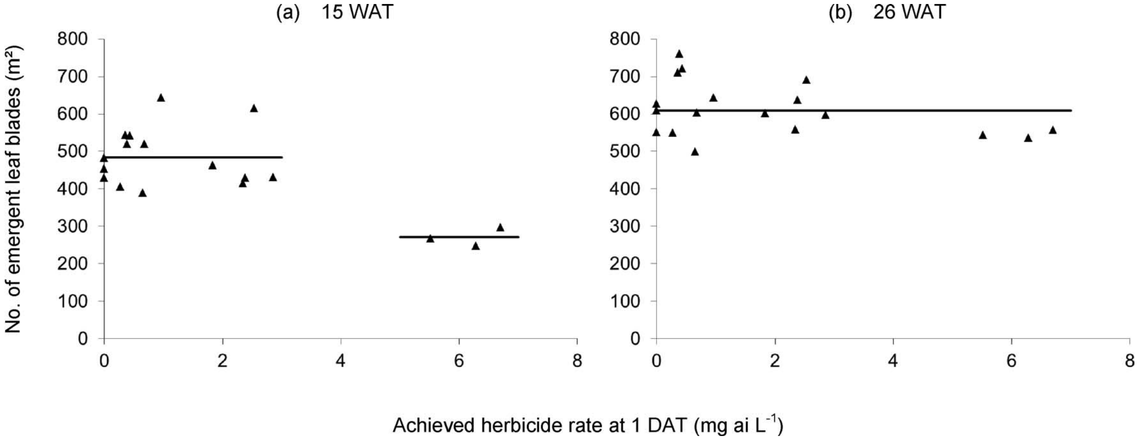

Figure 3. Response of the number of emergent delta arrowhead leaf blades to endothall rate at 15 and 26 wk after treatment. The equation for (A) is *Number of emergent leaf blades* = 22.0, when rate < 3; and *Number of emergent leaf blades* = 16.5, when rate > 5. The equation for (B) is *Number of emergent leaf blades* = 24.7, at any rate. Each symbol represents one plot.

the plant but not the crowns. This was observed during harvesting, where plants in the plots treated with high endothall concentrations consisted of intact crowns with little foliage above the sediment surface. However, higher rates of herbicide reduced the number of phyllodial plants (Figure 2). The general linear model predicted that, at 5 mg ai L^{-1}, phyllodial plants would be reduced by 68%.

At 15 WAT, control was evident, with the general linear model predicting a 44% reduction in the number of emergent leaf blades at 5 mg ai L^{-1} compared with lower concentrations. However, by 26 WAT, differences in the number of emergent leaf blades among all plots was not detectable ($P = 0.50$, Figure 3) because plants had regrown to similar levels in each plot. Although counts of emergent leaf blades are only a proxy for biomass, these results do provide a measure of delta arrowhead abundance that can be used as an indicator of channel obstruction.

Static-water mesocosm trials in the United States to determine native species susceptibility to endothall dipotassium salt showed severe damage to common arrowhead (*Sagittaria latifolia* Willd.) at 2 and 5 mg ai L^{-1} when exposed for 120 h during the growing season (29 C), 6 WAT (Skogerboe and Getsinger 2001).

The results presented here can be compared with previous findings by Clements et al. (2013) in which delta arrowhead biomass was reduced by $> 95\%$ with endothall applied at 7.4 mg ai L^{-1} to a static irrigation channel in winter, in which an exposure time of > 32 d was achieved. The elevated rates and extended exposure period can explain the greater level of control achieved by Clements et al. (2013) compared with the biomass reduction reported in the current study at 5 mg ai L^{-1} (69 and 92% biomass reduction for petiolate and phyllodial plants, respectively), with an exposure time of 21 d. Together, these trials demonstrate that, although endothall does not kill delta arrowhead outright, it leads to a substantial reduction in standing, aboveground, petiolate plant biomass and eliminates a high proportion of phyllodial plants. This will reduce channel impedance substantially by reducing the volume of the water column occupied by delta arrowhead during the spring irrigation period.

Reducing the number of phyllodial plants is important because these plants can transform to petiolate plants, which obstruct water flows to a greater degree, and produce seed for potential dispersal. Adair et al. (2012) also described that, where water levels can be maintained at depths greater than the transition point from submersed phyllodial to emergent petiolate forms (50 cm), the effect of damaging emergent forms can be reduced. However, this is not practical in many channels. Therefore, winter application of endothall provides a technique that can target both submersed and emergent delta arrowhead growth forms.

Under current management techniques in southeast Australia, which aim to minimize channel impedance, two foliar applications of glyphosate per year are typically required in channels that are heavily infested with delta arrowhead: one in spring and one in late summer. However, it is difficult for weed managers to conduct all herbicide applications at these times because of the extent of channels infested with delta arrowhead (M. Finlay, pers. comm.). A window of opportunity exists in winter when foliar herbicide applications are not carried out, where endothall application can be used in place of a spring glyphosate application to reduce channel impedance through the spring irrigation period. This would allow more efficient delivery of water during the spring irrigation period and spread the workload for weed managers more evenly through the year.

In summary, winter applications of endothall dipotassium salt in static water conditions provide a useful tool to reduce delta arrowhead biomass in irrigation channels during the spring irrigation period in southern, temperate regions of Australia. Although this study focuses on the efficacy of endothall on delta arrowhead biomass reduction, the ability of winter applications of endothall to disrupt formation of reproductive propagules needs further elucidation to inform long-term management objectives.

SOURCES OF MATERIALS

[1] Cascade®, United Phosphorus Inc., 630 Freedom Business Center Dr., King of Prussia, PA 19406.

[2] RaPID Assay® Endothall Test Kit, Strategic Diagnostics Inc., 128 Sandy Dr., Newark, DE 19713.

[3] Hach 2100Q® Portable Turbidimeter, Hach Company, 5600 Lindbergh Dr., Loveland, CO 80538.

[4] HOBO U20® Water Level Data Logger, Onset Computer Corp., 470 MacArthur Blvd., Bourne, MA 02532.

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