J. Aquat. Plant Manage. 60: 39–47

Operational-scale validation of a winter-use pattern for endothall to control submersed aquatic weeds in ponded Australian irrigation canals

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ABSTRACT

Endothall was applied to irrigation canals in three irrigation areas in Australia to validate, at an operational scale, a recently developed winter-use pattern to control two submersed aquatic weeds, namely, ribbon weed (*Vallisneria australis* S.W.L. Jacobs & Les) and floating pondweed (*Potamogeton sulcatus* A. Benn). Applications of either amine endothall or dipotassium endothall were made in the austral winter of 2017 (June–July), in ponded irrigation canals during the irrigation off-season. The target concentrations were 2.4 mg acid equivalent (ae) L^{-1} for amine endothall and 4.8 mg active ingredient (a.i.) L^{-1} for dipotassium endothall, with an exposure period of 3–10 wk. Reference pools, with no herbicide, were selected upstream of pools receiving herbicide or in adjacent canals. Restricted maximum-likelihood models were developed that showed both endothall formulations were effective at reducing ribbon weed percent volume occupied, stem length, and relative frequency in irrigation canal pools compared to untreated ribbon weed in the reference pools. Regrowth was greater in the pools treated with amine endothall than those treated with dipotassium endothall. These responses were consistent across the three irrigation areas and lasted for at least 33 wk of the 40-wk irrigation season. Floating pondweed abundance was also reduced substantially after the application of endothall, over the same period. We conclude that effective control of these submersed weeds in irrigation canals 1) can be achieved using the winter-use pattern, 2) can be achieved with either formulation of endothall (thus allowing the ecologically safer dipotassium endothall to be used), 3) can be achieved at operational scales, 4) is consistent across multiple geographic locations, and 5) lasts at least a full irrigation season.

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Key words: amine endothall, aquatic herbicide, aquatic weed control, dimethylalkylamine salt of endothall, dipotassium endothall, dipotassium salt of endothall, irrigation channel, *Potamogeton sulcatus*, submersed aquatic vegetation, *Vallisneria australis*.

INTRODUCTION

Submersed aquatic plants are widespread in earthen irrigation canals and, when abundant, they reduce the water-carrying capacity of the canals such that delivery of water to irrigators is reduced (Bakry et al. 1992, Bentivegna and Fernandez 2005, Dugdale et al. 2013, Clements et al. 2015). In Australia, these submersed plants are routinely controlled to restore flow capacity with the herbicide acrolein, winter dewatering, and/or mechanical excavation (Dugdale et al. 2013). Acrolein is effective on a wide range of species, but it only provides short-term control, is very toxic to fauna, and is dangerous to people applying it (Bowmer et al. 1992). Dewatering and mechanical removal can be effective, but these approaches to weed control are difficult to manage and are costly.

Endothall is a herbicide available for aquatic weed control as the dimethylalkylamine salt of endothall formulation and the dipotassium salt of endothall formulation, hereafter amine endothall and dipotassium endothall, respectively. Both formulations are based upon an endothall acid backbone and associated potassium and amine molecules, which disassociate upon dissolution in water (Sprecher et al. 2002). Endothall is a protein phosphatase inhibitor, although its exact mechanism for doing this is yet to be clarified (Tresch et al. 2011). The dipotassium endothall has very low toxicity to invertebrates and is 200–400 times less toxic to fish than amine endothall, which is toxic at concentrations that overlap with those used for weed control (Keckemet 1969, Sprecher et al. 2002). However, amine endothall is accepted to be more effective at removing weeds than dipotassium endothall (MacDonald et al. 2003, Gettys et al. 2014), although the reason for the greater potency of amine endothall is not understood (MacDonald et al. 2003). Consequentially, use of amine endothall is restricted to waterbodies where fisheries are not an important resource, such as irrigation canals, and is rarely used in natural surface waters (Slade et al. 2008). In contrast, dipotassium endothall can be used in a wide range of waterbodies (Sprecher et al. 2002).

Endothall has been widely used to manage submersed weeds and algae in a range of aquatic habitats since 1960 in the United States (Getsinger et al. 2008) and since 2004 in New Zealand (Wells and Champion 2010). In the United States, both amine and dipotassium formulations are used in flowing irrigation canals (Price 1969, Corbus 1982, Sisneros et al. 1998, Sprecher et al. 2002, Mudge et al. 2015) where they are used without an irrigation withholding period. In these situations, endothall is injected into flowing canals for a period of hours. The endothall solution then moves downstream as a slug, resulting in exposure of the weeds for a time approximately equal to the injection period. In Australia, irrigation withholding period restrictions imposed by the regulatory authority prevent endothall use in flowing irrigation canals during the irrigation season. Therefore, an alternative use pattern for endothall has been developed for use in Australian irrigation canals (Clements et al. 2013, 2015, 2018).

In Australia, current irrigation withholding period restrictions can only be complied with by applying endothall during the irrigation off-season, when water is ponded for ~12 wk during winter and irrigation water is not supplied. This method of application is termed the winter-use pattern of endothall (Clements et al. 2018). This method provides an opportunity for longer exposure times of endothall, because of ponded water coupled with slow decay, compared with endothall application in flowing irrigation canals during the irrigation season (Clements et al. 2015).

Research on the winter-use pattern of amine endothall shows that this use pattern provides control of key aquatic weeds that obstruct Australian irrigation canals, including ribbon weed (*Vallisneria australis*), floating pondweed (*Potamogeton sulcatus*), Canadian pondweed (*Elodea canadensis Michx.*), delta arrowhead (*Sagittaria platyphylla* (Engelmann) J.G. Smith), and robust water-milfoil (*Myriophyllum papillosum* Orchard) in laboratory dose-response trials (Clements et al. 2018). The novel winter-use pattern has also been assessed in small-scale field trials for ribbon weed, delta arrowhead, and robust water-milfoil (each consisting of three irrigation canal pools). Substantial biomass reduction was achieved for the latter two species, but the evidence for ribbon weed biomass reduction is equivocal. Given that ribbon weed is the most widespread and problematic weed obstructing Australian irrigation canals, this represents a major gap in our evidence of its efficacy for operational use. A further gap in the research by Clements at al. (2018) is scale. Although amine endothall was effective in laboratory and pilot-scale situations, for it to be used widely by canal managers, larger-scale trials were needed.

To fill this gap, we undertook trials in 24 km of earthen irrigation canals in Victoria and New South Wales (34–36°S), Australia, to validate the effectiveness of the winter-use pattern of amine endothall as a tool to clear irrigation canals of submersed aquatic weeds. We also evaluated the efficacy of dipotassium endothall to provide an ecologically safer alternative.

MATERIALS AND METHODS

Study area and submersed vegetation characteristics

The study was conducted in seven irrigation canals (covering a total length of 24 km) in three irrigation areas (Central Goulburn, Torrumbarry, and Coleambally) managed by Goulburn-Murray Water (in Victoria) and Coleambally Irrigation (in New South Wales). Pools, defined as a length of canal between two adjacent flow-regulating structures, were selected within irrigation canals. Pools selected for endothall application were nominated by the irrigation authority on the basis that ribbon weed and floating pondweed were present and deemed problematic and that endothall-treated water could be managed to comply with the conditions of APVMA (Australian Pesticides and Veterinary Medicines Authority: permit PER 14141). Reference pools, with no herbicide, were selected upstream of pools receiving herbicide or in adjacent canals.

Submersed aquatic vegetation (SAV) in these systems was dominated by ribbon weed, which is widespread in the irrigation canal systems of Victoria and New South Wales. It is native to Australia and is found widely in coastal and inland areas of southeast Australia (Jacobs and Frank 1997, Les et al. 2008, Salter et al. 2008). Ribbon weed requires shallow water with stable water levels (Blanch et al. 1999), which are provided by the irrigation canals. Floating pondweed is also native to Australia and is widespread in creeks, lagoons, and irrigation canals of the Murray-Darling River system (Flora of Victoria, 2014). It has long trailing stems (up to about 3 m) with large emergent and submersed leaves, which together form dense stands. Previously *Elodea canadensis* was also widespread in the irrigation areas of Victoria and New South Wales (Bowmer et al. 1995), but has declined substantially in recent years for unknown reasons. *Egeria densa* Planch. has recently become established in the Murray Valley irrigation area of Victoria, where it is rapidly spreading. These submersed species are managed to reduce their abundance and to return the water delivery capacity of the canals (Bill 1969, Dugdale et al. 2013).

Research design and submersed aquatic vegetation assessment

To determine the effectiveness of endothall on ribbon weed and floating pondweed, SAV was quantified within standardized plots within 20 pools or irrigation canals before and after the period of endothall application. Irrigation areas, canals, pool characteristics, endothall exposure and SAV characteristics of the pools are summarized in Table 1. Amine endothall was applied in eight pools, dipotassium endothall was applied in five pools, and no endothall was applied in seven reference pools. Reference pools were located in each irrigation area upstream of pools receiving herbicide or in an adjacent canal. The reference pools were selected so that they contained SAV in similar quantities to the pools with endothall applied.

SAV was quantified before endothall application (May 2017) and at three intervals after endothall application, in September 2017 (early spring), November 2017 (late spring),

Table 1. Pools used in this study and associated parameters. Water temp = mean water temperature over exposure period (not measured in all pools); endothall conc = acid equivalent (AE) concentration for amine endothall and active ingredient (a.i.) concentration for dipotassium endothall; initial = 1 d after application; average = over the exposure period; RW = ribbon weed; FPW = floating pondweed; RF = relative frequency (%); pre = before endothall application.

Irrigation Area	Canal Name	Plot	Canal Type	Length (km)	Width (m)	Depth (m)	Treatment	Endothall Concentration ($mg L^{-1}$) Nominal	Initial	Average	Exposure Time (wk)	Water Temp (C)	RW RF Pre	FPW RF Pre
Coleambally	Boona 7	2	Secondary	1.37	6–9	0.7–1.0	Amine	2.4	4.27	2.84	3		0.93	0.00
−34.88404,	Boona 7	3	Spur	1.28	6–9	0.7–1.0	Amine	2.4	1.48	1.47	3	9.6	0.10	0.84
145.89143	Boona 9	1	Secondary	0.98	6–9	0.7–1.0	Amine	2.4	5.05	4.89	3	8.6	0.49	0.42
	Boona 9a	1	Spur	0.75	6-9	0.6–0.7	Reference	0			N/A		0.77	0.00
	Boona 12	1	Secondary	0.38	8-11	0.7–1.1	Reference	0			N/A		0.56	0.00
	Boona 12	2	Spur	0.82	8-11	0.7–1.1	Reference	0			N/A		0.88	0.00
Torrumbarry	3/17/2	1	Secondary	2.68	8–11	0.5–0.75	Amine	2.4	1.83	1.27	10	9.0	0.98	0.22
−35.64598,	3/17/2	2	Secondary	1.52	8–11	0.5–0.75	Amine	2.4	2.32	1.46	10		0.95	0.24
144.00586	7/2	1	Secondary	1.3	6–7	0.5–0.75	Dipotassium	4.8	3.73	2.89	10	9.6	0.32	0.00
	7/2	2	Secondary	1.0	6–7	0.5–0.75	Dipotassium	4.8	4.41	3.23	10		0.83	0.00
	2/4/7/2	1	Spur	0.9	8–11	0.5–0.70	Reference	0			N/A		0.98	0.02
	7/12/2	1	Spur	0.6	8–11	0.5–0.65	Reference	0			N/A		0.56	0.00
Central Goulburn	5/3	1	Secondary	0.8	6–8	0.6–1.0	Dipotassium	4.8	3.60	5.43	8		0.48	0.29
−36.29520,	5/3	2	Secondary	1.28	6–8	0.6–1.0	Dipotassium	4.8	3.86	2.46	8	9.0	0.34	0.00
145.03691	5/3	3	Secondary	1.21	6–8	0.6–1.0	Dipotassium	4.8	1.46	2.43	8		0.24	0.00
	3	1	Secondary	1.41	8–12	0.5–1.1	Amine	2.4	5.27[1]	3.26	9		0.44	0.00
	3	2	Secondary	0.66	8–12	0.5–1.1	Amine	2.4	2.54	2.41	9		0.92	0.00
	3	3	Secondary	0.8	8–12	0.5–1.1	Amine	2.4	4.49[1]	1.67	9		0.49	0.00
	5/3	1	Secondary	1.38	6–8	0.6–1.0	Reference	0			N/A		0.29	0.00
	3	1	Spur	0.8	8–11	0.5–0.7	Reference	0			N/A		0.75	0.00

and March 2018 (fall). The three monitoring events after endothall application corresponded to 4–8 wk, 12–19 wk, and 31–33 wk, respectively, after the irrigation season had started (the range of values is due to assessments occurring over multiple weeks). SAV was assessed in all canals at 10 fixed transects in each pool, with each transect marked by a permanent stake driven into the ground. These cross-canal transects were established in a stratified random layout, with one transect positioned randomly within each of 10 blocks that were 50 m long to create a plot measuring up to 500 m. The start point for each plot was set 50 m downstream of the upstream flow regulator or associated infrastructure. SAV was assessed along each transect by wading across the canal adjacent to the transect, on the downstream side. Point intercept sampling occurred across each transect by temporarily lowering a pole vertically into the water column at 1-m intervals. At each point the species of plant that touched the pole was recorded, along with the height above the sediment that the plant touched the pole. In addition, the length and water depth of the intercepting leaf or stem (depending on growth form) were recorded. Relative frequency of each species was calculated as the percentage of point intercepts with the species present. The plant height and water depth at each point intercept was used to calculate the percent volume occupied (PVO) by the submersed plant, that is, a plant that has a canopy height of 0.6 m at a point where the water is 1.0 m deep has a PVO of 60%.

Water quality

At each of the vegetation assessment dates water quality parameters were recorded from the middle of the water column at each pool. Temperature (C), pH, electrical conductivity (EC, μS/cm) and dissolved oxygen (DO, mg/L) were determined using a Hach HQ40D Portable Multi Meter.[1] Turbidity (NTU) was measured using a Hach 2100Q Portable turbidimeter.[2] A temperature logger (HOBO U20 Water Level Data Logger[3]) was also deployed near the bottom of at least one pool from each irrigation area.

Endothall application

Applications of either amine endothall[4] or dipotassium endothall[5] were made in June–July 2017. Endothall was applied in winter, during the irrigation off-season, when pools contained standing water at their normal operating level. The target concentrations were 2.4 mg acid equivalent (ae) L^{-1} for amine endothall and 4.8 mg active ingredient (a.i.) L^{-1} for dipotassium endothall with an exposure period of 3–10 wk (Table 1).

For the Central Goulburn and Torrumbarry irrigation areas, the volume of each pool was calculated and then an appropriate volume of endothall was diluted with water (three parts water to one part herbicide) and immediately applied to the water surface using a truck-mounted boom sprayer with nozzle output calibrated to deliver a set volume commensurate with speed, or a handgun targeted into the center of the canal. At Coleambally, the volume of each pool was calculated and then an appropriate volume of undiluted endothall was applied to the water surface along the length of the canal with a handgun sweeping from side to side of the canal. Prior to endothall application, the upstream and downstream flow regulators of each pool were closed to prevent movement of endothall out of the pools. Approximately 3–10 wk after endothall application, depending on site, the canals were returned to operational status; that is, flow regulators were opened and the canals returned to delivering water. This determined the exposure period (Table 1).

To determine achieved endothall concentration and degradation, single water samples were taken from each endothall-treated pool at 1 d after endothall application and then at approximately weekly intervals until the exposure period ended. Endothall acid concentration was determined by liquid chromatography–mass spectrometry (LC-MS) (Islam et al. 2018).

Statistical analyses

Average PVO, average stem length, and relative frequency of occurrence of ribbon weed were calculated for each monitoring event for each of the 20 pools in the study. Prior to analysis, the mean ribbon weed PVO of each pool at each monitoring event after endothall application was angularly transformed, and the mean ribbon weed stem length of each pool was square-root transformed, so that the residual variation did not vary as the mean PVO and the mean stem length increased. For each monitoring event after endothall application, and each of the three measurements (angularly transformed mean PVO, square root of mean stem length, relative frequency of occurrence), the value of the measurement of each pool was jointly related to endothall application (none, amine, or dipotassium endothall), pre-endothall application value of the measurement, irrigation area, and canal type (secondary or spur), using a restricted maximum likelihood (REML) mixed-model analysis. The pre-endothall value for PVO was not angularly transformed, but the pre-endothall value for stem length was square-root transformed. In all these analyses the designated canal associated with each pool was a priori included as a random effect, to account for systematic spatial/management variation. When the designated canal random effect variance was estimated to be less than zero this was allowed to stand, in accord with standard practice when analyzing experimental designs. Fixed-effect model terms were included or excluded in a parsimonious model using Wald *F* tests. In cases where the calculation of the denominator degrees of freedom for the Wald *F* test failed numerically, the test was replaced by a parametric bootstrap test on the same *F* statistic. Differences in the residual variance between endothall formulation (none, amine, or dipotassium endothall) were examined using a χ^2 change in deviance test, because, with some monitoring events, the consistency of response differed between endothall formulation. For ease of presentation, the χ^2 change in deviance test results, for difference in residual variance with endothall, are presented as an equivalent *F* value with infinite denominator degrees of freedom (F value $= \chi^2$ value $\div$ [χ^2 degrees of freedom]). All statistical analyses were carried out using the REML directive and the VBOOTSTRAP procedure in GenStat 18 (VSN International, 2015). For mean ribbon weed PVO and stem length, response curves are presented using the backtransformed values of predicted values on the transformed scale.

Average PVO, average stem length, and relative frequency of floating pondweed were also calculated at each of the monitoring events, for each of the six pools that had a reasonable amount of floating pondweed present prior to endothall application. The results are presented graphically for these six pools.

RESULTS AND DISCUSSION

Endothall concentrations

Average initial amine endothall concentrations across the pools, and average over the exposure period, were 3.40 and 2.4 mg ae L^{-1}, respectively, which were close to the target concentration of 2.4 mg ae L^{-1}. Average initial dipotassium endothall concentrations across the pools, and average over the exposure period, were 3.41 and 3.3 mg a.i. L^{-1}, respectively, which were somewhat lower than the target concentration of 4.8 mg L^{-1}. At an individual pool level, endothall concentration varied (Table 1), most likely because of inaccuracies in measuring pool volumes at the time of endothall application, combined with limited lateral and longitudinal sampling along the length of the pool (only a single sample was taken per pool per sampling date). Mean water temperature during the exposure period was $<$10 C for most pools (Table 1), resulting in little endothall decay, as observed previously when endothall has been used in winter (Clements et al. 2015, 2018). Water-quality characteristics during the SAV monitoring events for each irrigation area are shown in Table 2.

Ribbon weed was common (preapplication relative frequency $\geq$0.1) in all irrigation canal pools while floating pondweed was common (preapplication relative frequency $\geq$0.1) in only five pools (four treated with amine endothall and one with dipotassium endothall; Table 1). *Nitella* sp. was in most pools at all monitoring events but was restricted to the shallow margins.

Ribbon weed response to endothall

The parsimonious models for angularly transformed ribbon weed PVO and ribbon weed relative frequency at all three postapplication monitoring events and the square root of ribbon weed stem length at the third postapplication monitoring event included separate linear responses to the preapplication value of the corresponding measurement, for the reference and the two endothall formulation treatments combined (Tables 3–5). The parsimonious models for stem length at the first and second postapplication monitoring events included parallel linear responses to the preapplication value of the corresponding measurement, for the reference and the two endothall formulation treatments combined. In addition, separate model intercepts for the two formulations of endothall (amine and dipotassium) were included for PVO and relative frequency at the second and third postapplication monitoring events. Separate residual variation for each of the three endothall treatments (amine, dipotassium, and reference) were included for relative frequency at the second postapplication monitoring event and for PVO, stem length, and relative frequency at the third postapplication monitoring event.

Table 2. Water-quality measures and values by irrigation area. Each value represents the mean of measurements taken at each of the amine endothall, dipotassium endothall, and reference plots during the four assessment events. N = number of samples; NTU = nephelometric turbidity units; DO = dissolved oxygen; EC = electrical conductivity; SD = standard deviation between four assessment events.

Irrigation Area	Assessment Event (*n*)	Turbidity (NTU)	Secchi (cm)	Temperature (C)	EC (μS/cm)	pH	DO (mg/L)
Coleambally	Pre May 2017 (7)	50	39	12.7	163	9.0	9.9
	Sep 2017 (7)	40	33	20.2	108	8.4	9.1
	Nov 2017 (7)	57	30	29.4	129	8.5	8.3
	Mar 2018 (7)	48	31	24.6	141	7.4	9.7
	Mean ± SD	48.8 ± 7.0	33.3 ± 4.0	21.7 ± 7.1	135.3 ± 23.0	8.3 ± 0.7	9.3 ± 0.7
Torrumbarry	Pre May 2017 (5)	170	26	9.3	122	7.8	9.7
	Sep 2017 (5)	159	15	11.1	125	7.9	9.4
	Nov 2017 (5)	137	20	19.6	132	7.9	7.8
	Mar 2018 (5)	99	20	20.1	93	7.7	9.0
	Mean ± SD	141.3 ± 31.3	20.3 ± 4.5	15.0 ± 5.6	118.0 ± 17.2	7.8 ± 0.1	9.0 ± 0.8
Central Goulburn	Pre May 2017 (13)	81	25	13.6	72	8.5	9.9
	Sep 2017 (13)	115	17	14.8	107	7.7	9.4
	Nov 2017 (13)	84	25	20.3	70	7.5	8.6
	Mar 2018 (13)	66	28	18.7	51	8.2	9.1
	Mean ± SD	86.5 ± 20.6	23.8 ± 4.7	16.9 ± 3.2	75.0 ± 23.3	8.0 ± 0.5	9.3 ± 0.5

Effects of irrigation area and canal type did not appear in any of the parsimonious models (Tables 3–5).

At the September 2017 monitoring occasion, 4–8 wk after the irrigation season had started, both endothall formulations were equally effective at reducing ribbon weed PVO, stem length, and relative frequency compared to the reference pools with similar initial weed infestation (Fig. 1). By November 2017, at the end of spring and 12–16 wk after the start of the irrigation season, and in March 2018 ribbon weed abundance remained suppressed in the endothall-treated pools compared to the reference pools with similar initial pre-endothall weed infestation, although the suppression was greater in the dipotassium endothall pools than the amine endothall pools. Although in March 2018 the weed infestation was still suppressed, the levels of PVO, stem length, and relative frequency were no longer related to the corresponding levels prior to endothall application (Fig. 1).

Together the ribbon weed PVO, stem length, and relative frequency data provide evidence that both formulations of endothall reduced ribbon weed substantially for the 33-wk period of the study (approximately 2 mo before the end of a full irrigation season). Some regrowth was observed during this time, and regrowth from amine endothall-treated pools was greater than from dipotassium endothall-treated pools. Although assessment of the vegetation did not occur after March 2018 (33 wk), anecdotal evidence from the irrigation agencies indicate that weed abundance remained low in all except two of these pools for several more months. These data provide evidence that this use pattern is effective at operational scales across a range of irrigation areas, with similar control achieved in each of the Central Goulburn, Torrumbarry, and Coleambally irrigation areas (it was not necessary to include irrigation area in any of the models; Tables 3–5).

For ribbon weed, results of the current study substantiate the results of previous mesocosm research and field pilot experiments on the winter endothall use pattern (Clements et al. 2018), where amine endothall was applied to standing water during winter (rates of 2.4–4.8 mg ae L^{-1} and 7–21 d exposure). Our results demonstrate that control 1) can be achieved at operational scales, 2) is consistent in multiple irrigation areas, and 3) lasts a full irrigation season (previous data extend to 19 wk). These findings therefore provide strong evidence that this use pattern can be employed by

Table 3. Tests of terms included in, and excluded from, the model for ribbon weed measurements at the first postapplication monitoring event in September 2017. XBefore represents (a) percent volume occupied (PVO) at preapplication monitoring for PVO model, (b) square root of stem length at preapplication monitoring for stem-length model, and (c) relative frequency at preapplication monitoring event for relative frequency model. *P* values < 0.05 are shown as bold.

	Angularly Transformed PVO			Square Root of Stem Length			Relative Frequency		
	Degrees of Freedom	*F* Value	*P* Value	Degrees of Freedom	*F* Value	*P* Value	Degrees of Freedom	*F* Value	*P* Value
Terms included									
Endothall presence (none vs. any)	Marginal term of model			1, 15.0	107.30	$\mathbf{3.1 \times 10^{-8}}$	Marginal term of model		
Response to XBefore	Marginal term of model			1, 16.3	11.19	**0.0040**	Marginal term of model		
Response to XBefore differs with endothall presence	1, 12.3	21.19	**0.00057**	Not in model			1, 11.4	4.79	0.050
Terms excluded									
Response to XBefore differs with endothall presence	In model			1, 12.5	1.98	0.18	In model		
Quadratic response to XBefore	1, 14.7	0.81	0.38	1, 12.2	2.21	0.16	1, 2.6	1.21	0.36
Endothall formulation	1, 7.5	2.64	0.15	1, 7.9	2.81	0.13	1, 6.4	1.90	0.21
Canal type (secondary vs. spur)	1, 14.6	0.00	0.97	1, 15.6	0.77	0.39	1, 14.5	0.15	0.70
Irrigation area	2, 14.0	4.18	**0.038**	2, 3.6	7.08	0.056	2, 2.7	1.50	0.37
Separate residual variation for each endothall formulation	2, ∞	0.47	0.63	2, ∞	0.11	0.90	2, ∞	1.64	0.20

Table 4. Tests of terms included in, and excluded from, the model for ribbon weed measurements at the second postapplication monitoring event in November 2017. XBefore represents (a) percent volume occupied (PVO) at preapplication monitoring event for PVO model, (b) square root of stem length at preapplication monitoring event for stem-length model, and (c) relative frequency at preapplication monitoring event for relative frequency model. P values < 0.05 are shown as bold.

	Angularly Transformed PVO			Square Root of Stem Length			Relative Frequency		
	Degrees of Freedom	*F* Value	*P* Value	Degrees of Freedom	*F* Value	*P* Value	Degrees of Freedom	*F* Value	*P* Value
Terms included									
Response to XBefore	Marginal term of model			1, 16.0	5.79	**0.032**	Marginal term of model		
Response to XBefore differs with endothall presence	1, 14.9	6.85	**0.019**	Not in model			1, 9.2	16.10	**0.0029**
Endothall formulation	1, 9.8	5.66	**0.039**	1, 13.1	5.73	**0.032**	1, 10.7	7.82	**0.018**
Separate residual variation for each endothall formulation	Not in model			Not in model			2, ∞	3.88	**0.021**
Terms excluded									
Response to XBefore differs with endothall presence	In model			1, 12.6	1.77	0.21	In model		
Response to XBefore differs with endothall formulation	1, 10.6	0.00	0.99	Marginal term not in model			1, 7.4	0.00	0.98
Quadratic response to XBefore	1, 11.3	0.54	0.48	1, 12.5	0.03	0.86	1, 2.5	7.58	0.086
Canal type (secondary vs. spur)	1, 11.9	0.01	0.91	1, 13.9	1.45	0.25	1, ?[1]	0.01	0.92[2]
Irrigation area	2, 3.4	0.72	0.55	2, 4.1	0.06	0.94	2, ?[1]	0.89	0.51[2]
Separate residual variation for each endothall formulation	2, ∞	0.43	0.66	2, ∞	0.87	0.42	In model		

[1]Numerical failure in calculating numerator degrees of freedom.
[2]Calculated using parametric bootstrap.

canal managers to control ribbon weed. Additionally, excellent control can be achieved with dipotassium endothall. Previous research showed ribbon weed was susceptible to dipotassium endothall, but further research in Australia has not been conducted (Dugdale et al. 2012). This formulation of endothall represents a major advantage, as dipotassium endothall is safer to use from an ecotoxicity point of view compared to amine endothall; that is, it has very low toxicity to invertebrates and is 200–400 times less toxic to fish than amine endothall (Keckemet 1969, Sprecher et al. 2002).

Amine endothall has previously been tested against ribbon weed in Australia (Bowmer and Smith 1984). Applications were made to flowing water in irrigation canals, as injections at 3–10 mg L^{-1} for 2–3 h to create a slug of treated water that moved downstream. Damage was apparent to ribbon weed, but only for a short distance downstream of the injection point (<1 km). It is not clear why ribbon weed control was good only for a short distance. In the United States endothall injections to canals are maintained for at least 6 h to provide sufficient exposure time. Based on this limited evidence it appears that the winter-use pattern provides greater efficacy than the in-season injection. Based on the success of in-season flowing water applications to control a range of SAV species in the United States (Price 1969, Corbus 1982, Sisneros et al. 1998, Sprecher et al. 2002, Getsinger et al. 2008, Mudge et al. 2015), it would be useful to test in-season control of ribbon weed in Australia again, except with longer exposure times. If proven to be effective, this would provide irrigation authorities greater flexibility to apply endothall to manage SAV during the season as excessive SAV growth becomes apparent.

Floating pondweed response to endothall

Floating pondweed PVO, stem length, and relative frequency substantially declined in the pools that received

Table 5. Tests of terms included in, and excluded from, the model for ribbon weed measurements at the third postapplication monitoring event in March 2018. XBefore represents (a) percent volume occupied (PVO) at preapplication monitoring event for PVO model, (b) square root of stem length at preapplication monitoring event for stem-length model, and (c) relative frequency at preapplication monitoring event for relative frequency model. P values < 0.05 are shown as bold.

	Angularly Transformed PVO			Square Root of Stem Length			Relative Frequency		
	Degrees of Freedom	*F* Value	*P* Value	Degrees of Freedom	*F* Value	*P* Value	Degrees of Freedom	*F* Value	*P* Value
Terms included									
Response to XBefore differs with endothall presence	1, 3.4	145.56	**0.00066**	1, 3.0	213.17	**0.00070**	1, 1.6	193.71	**0.012**
Endothall formulation	1, 8.0	4.18	0.075	Not in model			1, 7.8	6.33	**0.037**
Separate residual variation for each endothall formulation	2, ∞	8.45	**0.0021**	2, ∞	10.04	**0.000044**	2, ∞	10.85	**0.000020**
Terms excluded									
Endothall formulation	In model			1, ?[1]	1.59	0.098[2]	In model		
Response to XBefore differs with endothall formulation	1, 6.7	0.15	0.72	Marginal term not in model			1, 6.1	0.46	0.52
Quadratic response to XBefore	1, 3.1	1.026	0.39	1, 3.1	0.94	0.40	1, ?[1]	0.41	0.74[2]
Canal type (secondary vs. spur)	1, 5.5	0.27	0.62	1, 3.9	0.04	0.86	1, 3.6	4.57	0.11
Irrigation area	2, 3.2	3.91	0.14	2, 3.1	1.34	0.38	2, ?[1]	6.01	0.20[2]

[1]Numerical failure in calculating numerator degrees of freedom.
[2]Calculated using parametric bootstrap.

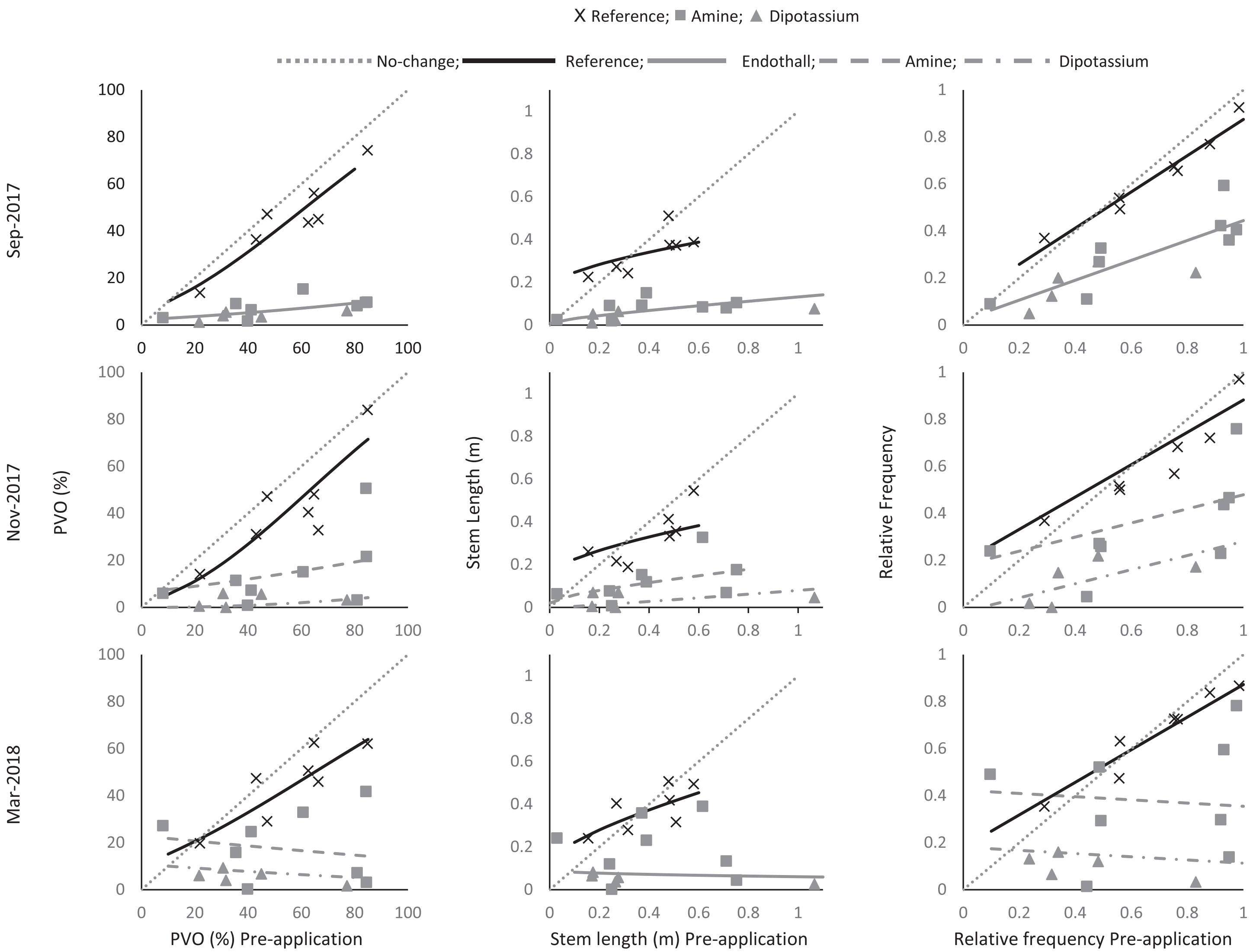

Figure 1. Response of ribbon weed percent volume occupied (PVO, y-axis, left column), stem length (y-axis, center column), and relative frequency (y-axis, right column) at each monitoring event compared to PVO, stem length, and relative frequency in May 2017 pre-endothall application (x-axis). Responses of endothall are combined, or split into amine or dipotassium endothall depending on the models developed in Tables 3– 5. Symbols = the mean value per pool; lines = predicted values.

endothall (Fig. 2), although there were no reference pools with reasonable amounts of ribbon weed at any monitoring event for comparison. This implies that, unlike the results for ribbon weed, the decline for floating pondweed can only be considered observational rather than causative. A feature of floating pondweed abundance is that, in contrast to ribbon weed, it continued to decrease in the pools treated with amine endothall with each successive monitoring event. Floating pondweed was widespread and abundant in each of the irrigation areas used during the study period (summer of 2017/2018). In fact, management activities were implemented to control it outside of our study pools, with either glyphosate or mechanical excavation. It is therefore likely that the reductions in relative frequency, PVO, and stem length that we observed in the endothall-treated pools were in fact due to endothall application.

Floating pondweed plants recorded at the September 2017 and November 2017 monitoring events generally consisted of an old, turgid stems that were defoliated, with small amounts of new foliage. These mature stems did not recover. Although endothall is considered a contact herbicide, a recent study suggests it may have systemic activity in aquatic weeds (Ortiz et al. 2019). The response of floating pondweed in our study is consistent with endothall having systemic activity. This is in contrast to the response of ribbon weed, which grew back at some sites, particularly those where amine endothall was applied.

Canal operation following endothall application

The ultimate demonstration of the effectiveness of endothall application on canal operation is that water conveyance in the canals is improved or maintained.

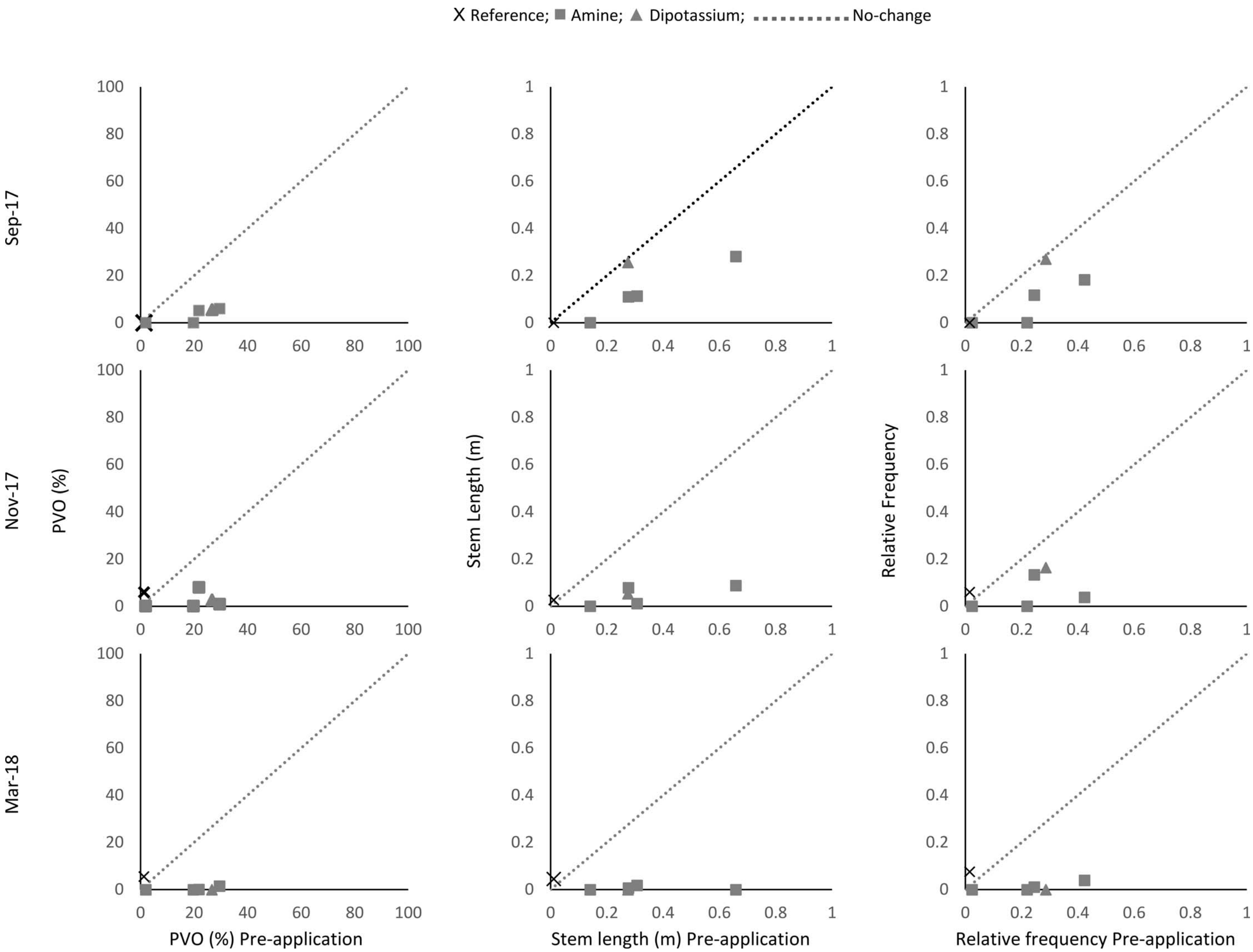

Figure 2. Mean floating pondweed percent volume occupied (PVO, y-axis, left column), stem length (y-axis, center column), and relative frequency (y-axis, right column) at each monitoring event compared to PVO, stem length, and relative frequency in May 2017 pre-endothall application (x-axis). Symbols = the mean value per pool; crosses = reference (no herbicide). Only includes pools where floating pondweed was present at the preassessment: Boona 7 plot 3, Boona 9 plot 1, CG 5/3 plot 1, Torrumbarry 3/17/2 plots 1 and plot 2, and Torrumbarry 2/4/7/2 plot 1—all others excluded.

Observations from canal managers indicate that canal operation had clearly improved at three of the six canals used in this study. Problems were not apparent in the remaining three canals because the demand for irrigation water (i.e., delivery of water ordered by farmers), either before or after application, was not great enough to challenge their flow capacity.

This research validates the effectiveness of a winter endothall use pattern, at an operational scale, for the management of ribbon weed in irrigational canals, and has provided prima facie evidence of similar effectiveness for floating pondweed. We conclude that effective control of these submersed weeds in irrigation canals 1) can be achieved with a winter-use pattern, 2) can be achieved with either formulation of endothall (thus allowing the ecologically safer dipotassium endothall to be used), 3) can be achieved at operational scales, 4) is consistent across multiple geographic locations, and 5) lasts at least a full irrigation season.

SOURCES OF MATERIALS

[1,2]HACH Company, Loveland, Colorado, USA.

[3]Onset Computer Corp., 470 MacArthur Blvd., Bourne, MA 02532, USA.

[4]Teton®, United Phosphorus Inc., 630 Freedom Business Center Drive, King of Prussia, PA 19406, USA.

[5]Cascade®, United Phosphorus Inc., 630 Freedom Business Center Drive, King of Prussia, PA 19406, USA.

ACKNOWLEDGEMENTS

This paper is dedicated to the memory of Shahidul Islam, who passed away on 13 May 2020.

This research was funded by Department of Agriculture and Water Resources, Agriculture Victoria, Goulburn-Murray Water, Coleambally Irrigation, Ord Irrigation, Murrumbidgee Irrigation, SunWater, and UPL Australia Ltd. The authors would like to thank the staff at Goulburn-Murray Water and Coleambally Irrigation whose cooperation and help was essential to undertake this trial, in particular, Kevin Kelly, Dannielle Ick, Russel Talbot, and Tim Nitschke.

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