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Response of fanwort (*Cabomba caroliniana*) to selected aquatic herbicides in New Zealand

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ABSTRACT

Fanwort (*Cabomba caroliniana* A. Gray, also known as cabomba) is an obligate submersed macrophyte native to the southern United States and Central and South America that has naturalized in the eastern United States, Canada, and various countries in Europe, Asia, and Oceania. It has been cultivated in New Zealand as an aquarium plant for at least 30 yr, but until recently (2009) had not naturalized. Fanwort is now declared an Unwanted Organism in New Zealand and as part of incursion response planning, effective management responses are required to achieve eradication. In this study we conducted herbicide trials on fanwort in containment using the herbicides carfentrazone, endothall, flumioxazin, and triclopyr. All four herbicides reduced fanwort biomass; however, with all herbicides viable plant material remained, indicating the potential for rapid regrowth after treatment, and a high degree of uncertainty of outcome where the herbicides are to be used for the management of field populations. None of the herbicides are recommended for use in eradication programs on fanwort without a clear understanding that multiple applications will likely be required, and there is a degree of uncertainty regarding the level of efficacy that can be achieved.

Key words: aquatic weed control, cabomba, carfentrazone, endothall, flumioxazin, triclopyr.

INTRODUCTION

Cabomba caroliniana A. Gray (fanwort, also known as cabomba) is an obligate submersed macrophyte native to Central America, South America, and the southern United States (Bultemeier et al. 2009). It has naturalized in the eastern United States (Bultemeier 2014), Canada, Malaysia, New Guinea, China, Japan, southern Europe, India, and Australia (Wilson et al. 2007). In the Northeast and Midwest of the United States fanwort behaves more like an invasive species (Bultemeier 2008) and less like a native that has found an expanded range. In New Zealand, it has been cultivated as an aquarium plant for at least 30 yr (Champion and Clayton 2001), but until more recently (2009) had not naturalized.

Fanwort is a perennial and primarily reproduces via vegetative fragmentation. Fanwort is not known to reproduce sexually in New Zealand, although reproduction by seed has been recorded in northern Australia (Schooler et al. 2006). Shoot fragments have a high regeneration potential (Dugdale et al. 2013a), a single-node fragment had 50% establishment success when planted in substrate and this increased to 100% for fragments with two or more nodes. Establishment success was lower for free-floating propagules, which had a 1 to 30% chance of colonization, depending on fragment size (Bickel 2017). As with other similar submersed invasive weeds, dispersal between water bodies is largely human mediated (Bickel 2015). Potentially, human-mediated spread by contaminated machinery, boats, and trailers or nets could disperse plants from the naturalized site in New Zealand.

Importantly, variation has been recognized amongst fanwort from different locations that is reportedly influenced by temperature and light (Bultemeier et al. 2009). In the United States, plants differ in color (green to red and intermediate) and respond differently to pH and temperature, both of which are parameters that influence photosynthesis and plant growth. "Green" fanwort had peak photosynthesis at pH 6.2, and was tolerant of a wide temperature range, including cool conditions expected for overwintering in the northeastern United States (Bultemeier 2008). By comparison the "red" and the "intermediate" ("aquarium") fanwort had peak photosynthesis at pH values of 5.9 and 6.5 respectively. Red fanwort had higher photosynthetic rates than both the intermediate and green fanwort phenotypes as temperature increased to 32 C (Bultemeier 2008).

Climate modelling suggests that fanwort could potentially grow in most lowland New Zealand water bodies (Champion and Clayton 2001). Fanwort can grow rooted in sediment, or free-floating in stagnant to slow flowing water, including streams, small rivers, lakes, ponds, and ditches, although it does prefer slightly acidic waters (DiTomaso et al. 2013). Fanwort was assigned an Aquatic Weed Risk Assessment score of 58 in New Zealand in 2001, but at that time it was considered premature to ban the species from sale and distribution based on its long cultivation history and lack of naturalization (Champion and Clayton 2001, Champion et al. 2007). However, it was recognized that locally, native species will be displaced where fanwort occurs and that uncontrolled populations of fanwort pose a threat if the continued spread of the plant occurs.

Until recently, fanwort was not managed in New Zealand (Champion et al. 2013). However, following the discovery of

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Table 1. Summary of effective herbicide treatments on fanwort. For each herbicide, target concentration rate, comments on efficacy and the cited literature is listed. Information is summarized and expanded on from Hackett et al. (2014) and DiTomaso et al. (2013).

Herbicide	Concentration	Efficacy Comments	References
Carfentrazone	100 μg ai L^{-1} to 2 mg ai L^{-1}	Not registered for use in water in New Zealand 60 to 90% biomass reduction in mesocosms Likely eradication of a field site	Bultemeier et al. 2009, Day et al. 2014, Hunt et al. 2015, Gettys et al. 2018
Diquat	0.3 to 2 mg ai L^{-1}	Approved for aquatic use in New Zealand Ca. 50% reduction of photosynthesis, limited efficacy on whole plants	Bultemeier 2008, Bultemeier et al. 2009, Dugdale et al. 2012
Endothall amine salt	1 to 5 mg ai L^{-1}	Not registered for use in water in New Zealand Ca. 86% biomass reduction Biomass reduction of 83, 100, and 100% at 0.5, 1.5, and 3 mg ai L^{-1}; 50% biomass reduction at 6.9, 2.8, and 0.3 h exposure period were obtained at 0.5, 1.5, and 3 mg ai L^{-1}	Bultemeier et al. 2009, Dugdale et al. 2012, Hunt et al. 2015
Endothall dipotassium	1 to 3 mg ai L^{-1}	Approved for aquatic use in New Zealand Symptoms within 3 to 7 d Less effective than endothall amine	Bultemeier et al. 2009, Dugdale et al. 2012
Florpyrauxifen-benzyl	10 to 20 μg ai L^{-1}	Not registered for use in water in New Zealand Ca. 90% reduction of biomass in mesocosms Not effective with static 4-wk exposure at 81 μg ai L^{-1} in mesocosm experiment	Gettys et al. 2018, Richardson et al. 2016
Flumioxazin	0.1 to 0.4 mg ai L^{-1}	Not registered for use in water in New Zealand Reduced photosynthesis in laboratory study, ca. 96% reduction of biomass of whole plant and field success	Bultemeier 2008, Bultemeier et al. 2009, Valent 2009
Fluridone	5 to 20 μg ai L^{-1}	Not registered for use in water in New Zealand Reduces biomass by > 80% after 84 d at 0.02 mg ai L^{-1} Exposure period – weeks	Mackey 1996, Nelson et al. 2001, 2002
Penoxsulam	0.1 to 0.2 mg ai L^{-1}	Not registered for use in water in New Zealand Exposure period – weeks Penoxsulam with diquat, ca. 90% reduction of biomass in mesocosms	DiTomaso et al. 2013, Gettys et al. 2018
Triclopyr	0.5 to 2.5 mg ai L^{-1}	Permitted for use in water in New Zealand, under Environmental Protection Agency controls and permissions Ca. 90% biomass reduction in mesocosms	DiTomaso et al. 2013, Gettys et al. 2018

an infestation (ca. 2.5 ha) in the Paremuka stormwater retention ponds, West Auckland, an incursion response has been enacted and fanwort declared an Unwanted Organism in 2016. Under this designation, it is an offense to propagate, sell, or distribute the species as the plant poses a major weed risk to New Zealand (New Zealand Government 2019).

Neither of the two herbicides currently registered for control of submersed aquatic weeds in New Zealand (diquat dibromide, endothall dipotassium salt) are particularly efficacious on fanwort. The effective chemical control options reported for fanwort internationally are limited to the amine salt of endothall (> 2.3 mg ai L^{-1} to 5 mg ai L^{-1}) and flumioxazin (200 to 400 μg ai L^{-1}), with lower (or variable) efficacy reported for carfentrazone, dipotassium endothall, diquat, florpyrauxifen-benzyl, fluridone, penoxsulam, and triclopyr (Table 1) (Moore 1991, Mackey 1996, Madsen 2000, Nelson et al. 2001, 2002, Bultemeier et al. 2009, van Oosterhout et al. 2009, Dugdale et al. 2012, DiTomaso et al. 2013, Bultemeier 2014, Hackett et al. 2014, Richardson et al. 2016). However, there are some contradictory efficacy results in the literature which could be due to differences in the scale of experimental trials (Hackett et al. 2014), or due to differences in the susceptibility of different fanwort phenotypes (Bultemeier 2008, Bultemeier et al. 2009). This highlights the importance of using plants sourced from the field site in New Zealand to assess efficacy.

The aim of this study was to understand the efficacy of several herbicides which have potential to effectively eradicate occurrences of this weed in New Zealand and mitigate further biosecurity concerns. We conducted an experiment in mesocosms to determine efficacy of herbicides against fanwort to guide subsequent eradication efforts in New Zealand.

MATERIALS AND METHODS

The effectiveness of four herbicides was tested on fanwort in a mesocosm study during summer (January to April 2017), at the National Institute of Water and Atmospheric Research experimental research facility, Hamilton, New Zealand (37°46′30.6″S; 175°18′45.12″E). Fanwort plant material collected from West Auckland (36°52′9.966″S; 174°18′45.119″E) was cultured in a greenhouse with 30% shade, in plastic tanks filled with municipal dechlorinated water and continuously aerated. One shoot (250 mm long) of fanwort was planted into each pot (375 ml) containing topsoil (1.3 g phosphorus: 3.6 g nitrogen per kilogram dry weight of soil), augmented with fertilizer[1] (N–P–K, 15.3–1.96–12.6; at label rate of 5 g L^{-1} soil) and topped with a layer of washed sand (10 mm). A total of 15 pots containing fanwort were placed in each of 25 experimental tanks (180 L). An additional 20 shoots of fanwort were prepared and oven dried to determine initial plant weight (0.218 ± 0.08 g SD). Water temperature and light was recorded (15-min intervals) over the experimental period with the use of pendant loggers[2] that were placed near the surface of the water in three randomly selected tanks. The pH[3] of the water was recorded in the morning and afternoon occasionally over the cultivation period, to provide an indication of the pH shift occurring in the tanks as pH is related to carbon availability to plants for photosynthesis.

After approximately 14 d in cultivation, ambient temperatures were 21 C (daily average) but there was still little new growth. Subsequently, CO_2 was delivered into the water through the aeration system. The CO_2 was gently bubbled through the tanks for a short period (ca. 1 h) every 2 to 3 d to provide plants with additional dissolved carbon (Nelson et al. 2002). One month after planting, fanwort had new shoots and shoot length had visibly increased with some shoots at the surface of the water. In response to increased algal growth in the tanks, the shade level was increased (80%).

Once fanwort was reaching toward the surface of the water in each tank (8-wk culture period), the selected herbicides were applied directly to the water column to maximize dispersal and contact with plant surfaces. The treatments were flumioxazin[4] (400 µg ai L^{-1}), carfentrazone[5] (2 mg ai L^{-1}), endothall dipotassium salt[6] (5 mg ai L^{-1}), and triclopyr[7] (2.5 mg ai L^{-1}). The treatments reflect maximum label rates of the active ingredients. It is noted that the maximum label rate for carfentrazone, as sourced,[5] exceeds the maximum on the label rate in the United States (0.2 mg ai L^{-1}). Treatments were replicated five times including untreated (no-herbicide) control tanks. Herbicides were applied at dawn, when the water pH was lowest. The water pH was recorded prior to treatment, 1 h after treatment and at midday, to provide an estimate of likely contact time for those herbicides (e.g., flumioxazin) that degrade more rapidly as pH increases (Netherland 2014).

Plant condition was visually assessed at weekly intervals posttreatment. Four weeks after treatment a destructive harvest of viable plant biomass was undertaken. At that time, damaged plant material had largely decayed, and new growth was initiating on some plants. Plant material was harvested from each tank, washed, and dried at 80 C until constant dry weight was achieved. Data are reported as fanwort dry weight biomass per tank for each treatment. Data were analyzed using ANOVA with Student's t post hoc tests. All mention of statistical significance refers to $P < 0.05$.

RESULTS AND DISCUSSION

Over the trial period water temperature in tanks ranged from 14 to 27 C with a daily average of 20.5 C. Light levels varied greatly over the growth and experimental period with seasonal change and the increased shade cloth used to reduce light and minimize algal growth. The average daytime light in midsummer was 1,182 µmol photons m^{-2} s^{-1} (under 30% shade cloth) and ranged from 426 to 176 µmol photons m^{-2} s^{-1} (under 80% shade) toward the end of summer. However, light was sufficient to support fanwort growth, as indicated by the surface-reaching growth of plants after approximately 6 wk. The largest range in pH values was recorded in January with a minimum of 5 (at 9 a.m.) and a maximum of 8 (at midday), with values more typically recorded between 6 and 7 and within the range suitable for fanwort growth (Mudge 2018). Prior to herbicide applications water pH averaged 6.6 ± 0.2 SD.

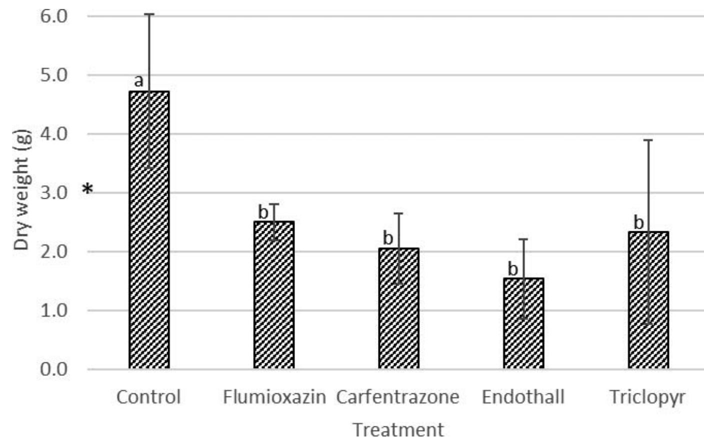

Figure 1. Fanwort biomass 4 wk after herbicide treatment. Solid bars represent average dry weight (g) from five replicate tanks, error bars represent 1 SD. Herbicide treatments include flumioxazin (400 µg ai L^{-1}), carfentrazone (2 mg ai L^{-1}), endothall dipotassium salt (5 mg ai L^{-1}), and triclopyr (2.5 mg ai L^{-1}). Letters represent significant differences between treatments (ANOVA; Student's t tests; $P < 0.05$). The asterisk (*) represents initial plant biomass per tank.

During the posttreatment period, plants in the untreated control tanks remained healthy and continued to grow with new shoots and buds observed. Fanwort did not show herbicide symptoms within the first week following any treatment. In tanks treated with endothall dipotassium salt and flumioxazin, a distinct discoloration of some plants was observed, whilst others were relatively unaffected 1 wk after treatment (WAT) within those treatments. By harvest, at 4 WAT, individual plants within tanks ranged from discolored to collapsed and fragmented. Similarly, some, but not all, plants treated with carfentrazone and triclopyr were fragmented whilst others remained intact. In contrast, the triclopyr-treated plants appeared to be intact, yet when they were touched most plants collapsed, presenting little structural integrity.

The highest biomass was recorded from untreated control tanks. All herbicides had a significant effect on fanwort biomass, reducing the amount of fanwort in the treated tanks compared with the untreated control tanks (Figure 1). However, biomass between herbicide treatments was similar, ranging from 47 to 67% reduction in biomass compared to the untreated control tanks.

Fanwort is sensitive to factors such as pH, water movement, and light levels in cultured conditions, as such the slow initial growth of fanwort in the experiment was not unusual. High pH levels (> pH 7) can strongly limit growth of fanwort (Mackey 1996, Nelson et al. 2002, Bickel 2015), with the optimum pH range being 5 to 6.5 (Bultemeier 2008, Schooler et al. 2009). In the experiment the addition of bubbling CO_2 and alternately bubbling air into the culture tanks with fanwort provided gentle water movement, dissolved carbon, and aided in keeping the water slightly acidic for optimum plant growth.

There are relatively few studies that have treated rooted fanwort plants with herbicides against which the present study can be compared. Additionally, varied susceptibility to herbicides was noted between different fanwort phenotypes, with green fanwort being the most tolerant (Bultemeier et al. 2009). Furthermore, the green fanwort phenotype differs from the fanwort population that has established in Auckland, which is also green (as opposed to red) but often tinged with purple and the undersides of the leaves were paler (P. D. Champion, unpub. data), potentially similar to the intermediate phenotype known from the aquarium trade in the United States (Bultemeier 2008). In addition to phenotype, plant age (length of time in cultivation) and length of time between treatments and harvest all vary in the literature. All these factors complicate comparisons from which to draw a greater understanding of herbicide efficacy. For example, although the herbicides in the present study all reduced the biomass of fanwort, only the use of carfentrazone resulted in an apparently similar response to that reported in the literature, with ca. 60% reduction (Bultemeier 2008, Hunt et al. 2015). However, the similar level of biomass reduction was achieved with different rates, i.e., 0.2 mg ai L^{-1} (Bultemeier 2008) compared with 2 mg ai L^{-1} in the present study. Gettys et al. (2018) noted an even lower rate of carfentrazone (0.1 mg ai L^{-1}) also resulted in a higher level of biomass reduction (ca. 90%) when left for 16 WAT. Of note, carfentrazone was applied at 2 mg ai L^{-1} to half of a small (ca. 8 ha), shallow (maximum depth, 2.7 m) lagoon in Australia, resulting in the putative eradication of fanwort (Day et al. 2014). Further, Dugdale et al. (2013b) suggest that carfentrazone, registered in Australia, can be useful for the control of fanwort.

In contrast, triclopyr was more effective (ca. 50% reduction in biomass, using 2.5 mg ai L^{-1}) than was reported by Bultemeier (2008) against green fanwort using a higher treatment rate. Green fanwort treated with triclopyr (4 mg ai L^{-1}) did not differ from the untreated control plants at 2 WAT (Bultemeier 2008). However, Gettys et al. (2018) used the same treatment rate as the present study (2.5 mg ai L^{-1}) and reports still greater efficacy of ca. 90% reduction.

Amongst the other herbicides, flumioxazin was not as efficacious in the present study as has been described in previous studies. For example, Valent (2009) reported 100% control with 200 μg ai L^{-1} flumioxazin at a field site (Hackett et al. 2014), and Bultemeier (2008) suggested that 400 μg ai L^{-1} flumioxazin provided the best control of green fanwort (the least susceptible phenotype). In the present study, there was only a 40% biomass reduction of fanwort with 400 μg ai L^{-1} flumioxazin. The efficacy of flumioxazin has reportedly been linked to the pH of the water (rapid breakdown occurs at high pH levels, ca. 15-min half-life at pH 9) and light penetration, although no evidence of an effect was reported by Bickel et al. (2018). Trials in Australia showed that fanwort was effectively controlled even if exposed to the herbicide for only 15 min (Bickel et al. 2018).

Endothall at 5 mg ai L^{-1} (dipotassium salt) provided ca. 67% biomass reduction. This contrasts with the findings of Bultemeier (2008), which did not consider endothall (dipotassium salt) at 3 mg ai L^{-1} to be efficacious, with similar conclusions reached by Dugdale et al. (2012) when using up to 5 mg ai L^{-1} endothall (dipotassium salt).

Genetic studies to elucidate which phenotype/s exist in New Zealand and internationally would enable greater comparisons to be made with previous studies. It is important to realize that if multiple phenotypes exist in New Zealand, employing a particular suboptimal control measure may select for more difficult to control fanwort in the future. Previous results have demonstrated clear phenotypic differences in response to herbicide treatments and lack of susceptibility of fanwort to most herbicides (Bultemeier et al. 2009).

In summary, challenges in comparing studies, including the recognized variability in the tolerance of different fanwort phenotypes to herbicides, highlights the importance of using plants from the local New Zealand infestation to assess herbicide efficacy relevant to a proposed eradication program. All four herbicides reduced fanwort biomass; however, in all treatments, the amount of viable plant material that remained indicates the potential for rapid fanwort regrowth after treatment. For a successful eradication program, multiple applications of the selected herbicides would likely be required, also noting a degree of uncertainty regarding the level of efficacy that could be achieved with the herbicides evaluated. Small-scale field trials are likely required to fully explore herbicide efficacy and the levels of fanwort biomass reduction that can be achieved.

SOURCES OF MATERIALS

[1]Osmocote fertilizer, Scotts Miracle-Gro Company, 14111 Scottslawn Road, Marysville, OH 43041.

[2]Hobo pendant temp/light logger (UA-002-64), Onset, 470 MacArthur Blvd, Bourne, MA 02532.

[3]EXO1 Multiparameter Sonde (SKU: 599501), 1700/1725 Brannum Lane, Yellow Springs, OH 45387.

[4]Flumioxazin (Valor® 500 WG Herbicide), Sumitomo Chemical Co., Ltd., 27-1, Shinkawa 2-chome, Chuo-ku, Tokyo 104-8260, Japan.

[5]Carfentrazone (Shark™) FMC Corporation, 2929 Walnut St, Philadelphia, PA 19104.

[6]Endothall (Aquathol® K), United Phosphorus Inc., 630 Freedom Business Center Dr, King of Prussia, PA 19406.

[7]Triclopyr (Garlon™ 360), Dow Corporate, 2211 H. H. Dow Way, Midland, MI 48674.

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