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Response of parrotfeather watermilfoil and alligatorweed to foliar florpyrauxifen-benzyl applications

ANDREW W. HOWELL, DEBORAH E. HOFSTRA, MARK A. HEILMAN, AND ROBERT J. RICHARDSON*

ABSTRACT

The emergent aquatic plants, parrotfeather watermilfoil [*Myriophyllum aquaticum* (Vell.) Verdc.] and alligatorweed [*Alternanthera philoxeroides* (Mart.) Griseb.] threaten native ecosystem services within invaded regions throughout the world. The registration of the auxin herbicide, florpyrauxifen-benzyl, in the United States provides water resource managers with another herbicide for weed control. Currently, available aquatic herbicides do not control these marginal weed species with consistency. Research was conducted in the United States (North Carolina) and New Zealand to evaluate foliar applications of florpyrauxifen-benzyl for parrotfeather watermilfoil and alligatorweed control. Greenhouse and outdoor mesocosm studies indicated single foliar applications of florpyrauxifen-benzyl provided $> 90\%$ parrotfeather watermilfoil control 4 and 8 wk after treatment (WAT) at rates ≥ 29.4 g ai ha^{-1}. Alligatorweed was less sensitive than parrotfeather watermilfoil at the same tested rates in both greenhouse and outdoor mesocosm environments, and repeat applications of florpyrauxifen-benzyl at 29.4 to 58.8 g ai ha^{-1} were necessary to achieve $> 94\%$ alligatorweed control 12 WAT. Both parrotfeather watermilfoil and alligatorweed plants displayed signs of recovery when exposed to the lowest herbicide rate (14.7 g ai ha^{-1}) evaluated. Therefore, operational florpyrauxifen-benzyl applications of < 29.4 g ai ha^{-1} are discouraged for herbicide resistance management. Future research should screen additional aquatic herbicides as potential tank mix partners for improving alligatorweed control longevity from a single florpyrauxifen-benzyl treatment. Water resource managers would additionally benefit from studies evaluating florpyrauxifen-benzyl foliar plus directed in-water application strategies to simulate common emergent plant control scenarios.

Key words: *Alternanthera philoxeroides* (Mart.) Griseb., aquatic, emergent, invasive, *Myriophyllum aquaticum* (Vell.) Verdc.

*First and fourth authors: Graduate Research Assistant, Professor, Department of Crop and Soil Sciences, North Carolina State University, Campus Box 7620, Raleigh, NC 27695. Second author: Programme Leader, National Institute of Water and Atmospheric Research, P.O. Box 11115, Hillcrest, Hamilton, New Zealand. Third author: Director of Aquatic Technology, SePRO Corporation, 11550 North Meridian St, Suite 600, Carmel, IN 46032. *Corresponding author's E-mail: rob__richardson@ncsu.edu. Received for publication December 8, 2021 and in revised form June 8, 2022.

INTRODUCTION

Aquatic plant invasions interfere with municipal and ecosystem services worldwide (Hussner et al. 2017). Marginal plant incursions are particularly detrimental for habitat quality, and limit the growth of desirable native plants through resource competition and displacement (Hofstra and Champion 2010). Furthermore, these invasive species promote vector-borne disease habitat (Orr and Resh 1989), restrict recreation opportunity, and obstruct intakes for water consumption and hydropower generation (Durden et al. 1975, Clayton and Champion 2006). Within invaded regions, some of the worst nonnative marginal plants are parrotfeather watermilfoil [*Myriophyllum aquaticum* (Vell.) Verdc.] and alligatorweed [*Alternanthera philoxeroides* (Mart.) Griseb.] (Clayton 1996).

Native to South America, parrotfeather watermilfoil is a sprawling marginal plant often forming monospecific floating mats in quiescent waters (e.g., ditch banks, shallow wetlands, and littoral edges) (Wersal and Madsen 2011). The feather-like leaves, typical of *Myriophyllum* spp., appear in both emergent and submersed forms, thus providing parrotfeather watermilfoil with additional resource availability and greater tolerance to water level fluctuations (Sutton 1985, Wersal and Madsen 2010). Outside the native range, parrotfeather watermilfoil reproduction relies solely on plant fragmentation (Sutton 1985), with rhizome and rooting tissues ensuring perennial success (Sytsma and Anderson 1993). These physiologic characteristics allow parrotfeather watermilfoil the ability to invade diverse aquatic environments and thrive in poor growing conditions (e.g., drawdown events, high turbidity, eutrophic settings) (Maltchik et al. 2007, Wersal et al. 2013). Once established, parrotfeather watermilfoil can be difficult to eradicate with limited management tools or control tactics. At present, parrotfeather watermilfoil is widely distributed throughout the United States and New Zealand after plants escaped from the aquarium trade (Sutton 1985, Hofstra et al. 2006).

Alligatorweed is a marginal, stoloniferous plant in the Amaranthaceae family, native to South America (Julien et al. 1995). A perennial species, alligatorweed is characterized by vigorous aquatic growth with dense roots or as a free-floating entangled mat, and can inhabit both aquatic and terrestrial environments (Dugdale et al. 2010). Vegetative propagation leads to alligatorweed invasion success outside of its native range (Dugdale et al. 2010), because fragmented stems readily develop adventitious roots from the nodes that provide anchorage at new sites (Langland 1986). Early-stage invasion requires prompt management, as established alligatorweed populations are difficult to control (Hofstra and Champion 2010). Alligatorweed is distributed throughout the southeastern United States following release from ship ballast in the late 1800s (Buckingham 1996), with localized dispersion found in the North Island of New Zealand since its incursion in the early 1900s (Champion and Clayton 2000).

Effective control methods for parrotfeather watermilfoil and alligatorweed are limited in part because of the previously described plant physiology characteristics, but also because of the inherent challenges of developing methods that are effective across aquatic and wetted-terrestrial invasion sites. Biological control agents such as grass carp (*Ctenopharyngodon idella*) and beetles (flea beetle [*Lysathia ludoviciana*]; alligatorweed beetle [*Agasicles hygrophila*]), have shown promise (Julien et al. 1995, Cilliers 1998, Garner et al. 2013); however, the effectiveness of management relies heavily on localized infestation and environmental conditions (i.e., suitable insect overwintering temperatures and reproductive ability to maintain biocontrol populations). Similarly, biological control deployment is strictly governed and will not be suitable among regions in which permitting restricts release (Clayton 1996, Hussner et al. 2017). Mechanical methods for parrotfeather watermilfoil and alligatorweed control can offer short-term biomass reduction, but the long-term effectiveness of mechanical techniques is limited because of plant reproductive strategies with increased disturbance (i.e., plant fragments contributing to new populations). Therefore, the most frequently utilized management approach for controlling these marginal weed species in the United States and New Zealand is with herbicides (Wersal and Madsen 2007, Hofstra and Champion 2010, Dugdale and Champion 2012).

Though frequently relied on, invasive plant control with herbicides is also limited by both the efficacy and availability of registered products. For example, New Zealand has just two registered aquatic herbicides, diquat dibromide (photosystem I inhibitor) and endothall dipotassium salt (protein phosphatase inhibitor), although glyphosate (EPSP inhibitor), imazapyr (acetolactate synthase inhibitor), and metsulfuron-methyl (acetolactate synthase inhibitor) applications do occur under special-use permitting (Hofstra and Champion 2010, NZ EPA 2012). The United States has a broader herbicide portfolio; however, not all available herbicides control parrotfeather watermilfoil and alligatorweed with consistency. Contact herbicides (e.g., diquat) are effective in providing short-term control of parrotfeather watermilfoil and alligatorweed, whereas systemic herbicides (e.g., glyphosate and imazapyr) often achieve longer periods of control (Wersal and Madsen 2007, Schooler et al. 2008, Hofstra and Champion 2010, Clements et al. 2014). The systemic herbicide imazapyr (acetolactate synthase inhibitor) at 584 and 1,123 g active ingredient (ai) ha^{-1} achieved complete control of parrotfeather watermilfoil in a 10-wk study (Wersal and Madsen 2007), whereas repeat applications of imazapyr at 0.16 to 0.64 kg ai ha^{-1} were required for alligatorweed suppression (Hofstra and Champion 2010). In a mesocosm study, Cox et al. (2014) found triclopyr at 3.36 and 6.72 kg acid equivalent (ae) ha^{-1}, and 2,4-D (synthetic auxin) at 1.06 and 2.13 kg ae ha^{-1} effectively reduced alligatorweed biomass $> 91\%$. Initial control of parrotfeather watermilfoil has also been achieved using similar rates of 2,4-D and triclopyr, though plant regrowth was reported to occur with single herbicide applications (Hofstra et al. 2006, Wersal and Madsen 2010). Although herbicide options do exist for managing these marginal species, repeat applications are generally required to meet management goals. There is a clear need to investigate additional herbicides as they become available.

In 2018, florpyrauxifen-benzyl (synthetic auxin) was registered for aquatic site applications in the United States as two available formulations (emulsifiable [EC] and soluble [SC] concentrates). Florpyrauxifen-benzyl is considered a reduced risk herbicide (U.S. EPA 2017) and has ca. ~ 100 times lower use rate than the aquatic auxin herbicides, 2,4-D and triclopyr. In a 4-wk study, initial dose–response screenings of florpyrauxifen-benzyl subsurface applications provided 50% effective concentration (EC_{50}) values of <0.3 μg ai L^{-1} for parrotfeather watermilfoil, and 0.96 to 1.8 μg ai L^{-1} (Richardson et al. 2016). A similar study investigating concentration and exposure time (CET) relationships indicated two submersed *Myriophyllum* spp. were controlled 30 and 60 d after treatment (DAT) when exposed to florpyrauxifen-benzyl 3.0 μg ai L^{-1} for 6 to 24 h (Beets et al. 2019). Foliar applications (which are economical and easy to apply) of select herbicides are generally more effective than submersed application methods when targeting marginal plant invaders. Although in-water herbicide concentrations are not directly comparable to foliar application rates, no difference in control was observed when parrotfeather watermilfoil plants were treated with maximum label rates of triclopyr as subsurface (2.5 mg ae L^{-1}) and foliar (6.7 kg ae ha^{-1}) applications (Wersal and Madsen 2010).

Currently, there has been no efficacy data published describing foliar applications of florpyrauxifen-benzyl for parrotfeather watermilfoil or alligatorweed control, and there remains a need to evaluate the effectiveness of this herbicide applied as a foliar solution to target frequently managed marginal plant invaders and potentially broaden the available herbicide options. Since both species are susceptible to other aquatic auxin herbicides (i.e., 2,4-D and triclopyr), we hypothesize parrotfeather watermilfoil and alligatorweed will be sensitive to the tested florpyrauxifen-benzyl rates. The objective of this research was to evaluate foliar rates of florpyrauxifen-benzyl to determine the control of parrotfeather watermilfoil and alligatorweed for water resource management in the United States and New Zealand.

MATERIALS AND METHODS

Greenhouse study

Trials were conducted at the North Carolina State University, Aquatic Weed Control Labs (Raleigh, NC) during a 4-wk study period and repeated in time (3 November and

5 December 2017, respectively). Alligatorweed and parrotfeather watermilfoil were propagated as 10-cm apical shoot tips and transplanted individually into 10 cm^2 (0.92 L) pots (i.e., one species shoot per pot) containing commercial potting media (Fafard® 2 Mix[1]). During transplant, Osmocote® slow-release fertilizer[2] (14–14–14) was incorporated into the planting media at a rate of 15 g per pot. Pots remained saturated throughout the experimental period via overhead mist irrigation system at 0.635 cm^{-1} of tap water, dispensed twice daily. Supplementary light was provided to simulate a photoperiod of 12 h d^{-1} with ambient temperature maintained at 27 ± 3 C. Plants were cultivated 14 to 28 d prior to treatment to allow for root establishment and allow for active shoot growth (one to two shoots per pot; shoots measuring 16 to 24 cm above soil line at treatment).

Herbicide treatments included three foliar applications of florpyrauxifen-benzyl emulsifiable concentrate (EC)[3] [SLF-9523] (29.4, 44.1, and 58.8 g ai ha^{-1}), and a nontreated control. Treatments were arranged as a randomized complete block design with four replications. Treatments were applied using a pressurized CO_2 spray chamber with a single Teejet® XR8003 nozzle[4] at 234 L ha^{-1} to the foliage of the target species. Visual ratings of percent control were made at 2 and 4 wk after treatment (WAT) on a scale ranging from 0% (no injury) to 100% (complete necrosis). Above-sediment plant biomass was harvested 4 WAT and dried at 60 C for 48 h prior to recording biomass (g dry mass).

Outdoor mesocosm study

Trials occurred at the National Institute of Water and Atmospheric Research (NIWA) Ruakura Campus, New Zealand on 10 January 2018 (New Zealand summer). Separate alligatorweed and parrotfeather watermilfoil experimental treatment containers were established using basal stem material (~ 10 to 15 cm in length; 15 stems per experimental unit) planted in 60-L plastic bins (bin surface area: 0.23 m^2), filled two-thirds with sediment, and covered with ~ 7 cm sand layer. Freshwater (pH 7.2) was added to each bin to occupy the additional space (~ 10 cm) in the mesocosm bin with water replenished throughout the study period. Plant establishment ensued 2 mo prior to herbicide treatment to promote active shoot growth and increase foliage cover (bin surface area: > 50% alligatorweed and > 80% parrotfeather watermilfoil). Treatment bins remained outdoors for the duration of the study with ambient temperature conditions of 18.5 ± 2 C.

Using the 2017 North Carolina greenhouse studies as a preliminary plant response reference, treatments included four foliar rates of the florpyrauxifen-benzyl EC formulation [SLF-9523] (14.7, 29.4, 44.1, and 58.8 g ai ha^{-1}), and a nontreated control. Treatments were arranged in a randomized complete block design with 10 replications for both plant species. Hasten ESO[5] (esterified seed oil) was also included in the spray solution at 0.5% v/v during plant treatment. Applications were made using a handheld pump sprayer with an application volume of 234 L ha^{-1}. At treatment application, five nontreated bins representing each species were destructively harvested to determine pretreatment biomass. Observations of auxin herbicide injury response and visual percent control estimates of exposed shoot material were evaluated throughout the study period as previously described for the greenhouse trials. At 6 WAT, alligatorweed regrowth occurred across all florpyrauxifen-benzyl rates tested, which initiated a retreatment to one-half of the replicates of the alligatorweed bins 8 wk after initial treatment (8 WAIT) to evaluate the effectiveness between a single and repeat florpyrauxifen-benzyl foliar application. The study duration lasted 8 wk for parrotfeather watermilfoil, and 12 wk for alligatorweed. Plant shoot and root biomass was harvested at the end of each species study and dried at 60 C for 72 h to obtain biomass dry weights.

Statistical analysis

Data from the greenhouse and mesocosm studies were subjected to analysis of variance (ANOVA), and Fisher's Protected LSD post hoc test if significant effects ($P < 0.05$) were observed using RStudio[6] 'base', 'agricolae', and 'dplyr' packages (R Core Team 2020, de Mendiburu 2020, Wickham et al. 2021). A significant interaction was detected between run and species for the greenhouse study ($P < 0.001$), where nontreated plants in the second run were approximately 1.5× larger than the nontreated plants in the first run. Thus, biomass reductions for the greenhouse study were analyzed by run. All other data were pooled across runs for the greenhouse studies.

RESULTS AND DISCUSSION

Greenhouse study

Initial injury of parrotfeather watermilfoil and alligatorweed occurred within 24 to 48 h after treatment (HAT) of florpyrauxifen-benzyl EC foliar applications, and appeared as terminal leaf and stem epinasty (twisting). Within 72 HAT, parrotfeather watermilfoil treated with florpyrauxifen-benzyl 29.4, 44.1, and 58.8 g ai ha^{-1} exhibited canopy collapse (wilting), chlorosis, and preliminary senescence. Alligatorweed also appeared chlorotic 72 to 96 HAT, with increased hyponasty (downward leaf convexity) when exposed to 44.1 and 58.8 g ai ha^{-1} rates of florpyrauxifen-benzyl.

All foliar rates of florpyrauxifen-benzyl rates provided > 95% control of parrotfeather watermilfoil by 2 wk after treatment (WAT) (Table 1). At 4 WAT, no visual control or plant biomass differences occurred as herbicide rate increased for parrotfeather watermilfoil (Figure 1). However, parrotfeather watermilfoil biomass reduction did differ between trial runs ($P < 0.05$), thus having a greater biomass reduction in the first trial run, which was likely attributed to initial biomass compared to run two. The average reduction in biomass compared to the nontreated control plants averaged 57.2 ± 3.7% and 46.2 ± 5.8% in Runs 1 and 2, respectively.

Alligatorweed was less sensitive to florpyrauxifen-benzyl treatments than parrotfeather watermilfoil; where visual control estimates were 72.5 and 31.9% less for alligatorweed

Table 1. Visual estimates of parrotfeather watermilfoil and alligatorweed control following foliar applications of florpyrauxifen-benzyl in the North Carolina greenhouse study.

	Parrotfeather (%)[2,3]		Alligatorweed (%)	
Treatment Rate (g ai ha^{-1})	2 WAT[1]	4 WAT	2 WAT	4 WAT
29.4	95.6 a	92.3 a	23.1 a	56.3 a
44.1	95.6 a	97.5 a	21.9 a	59.4 a
58.8	98.8 b	100.0 a	26.3 a	68.1 b
Nontreated control	0.0 c	0.0 b	0.0 b	0.0 c

[1]WAT: weeks after treatment.
[2]Control ratings based on visual estimates 0% (no injury) to 100% (complete desiccation).
[3]Means within columns followed by the same letter do not differ according to Fisher's Protected LSD ($P < 0.05$, $n = 4$).

than parrotfeather watermilfoil at the 58.8 g ai ha^{-1} rate (2 and 4 WAT assessments, respectively). Increased herbicide rate did result in greater alligatorweed injury (e.g., basal stem splitting and necrosis) from 2 to 4 WAT (Table 1). At 4 WAT, alligatorweed control with the 58.8 g ai ha^{-1} herbicide rate was different from the 29.4 and 44.1 g ai ha^{-1} florpyrauxifen-benzyl rates; however, there was no difference in alligatorweed control between the 29.4 and 44.1 g ai ha^{-1} rates at 4 WAT (Table 1). Conversely, there was no difference in alligatorweed biomass reduction at harvest (4 WAT) across the florpyrauxifen-benzyl rates tested (Figure 1). Similar to the parrotfeather watermilfoil studies, alligatorweed biomass reduction differed between runs ($P < 0.05$), with greater biomass reduction occurring in the first run. Treated plants averaged 63.1 ± 4.1% and 36.6 ± 8.1% in Runs 1 and 2, respectively at harvest. Nonetheless, alligatorweed treated with florpyrauxifen-benzyl at 29.4 and 44.1 g ai ha^{-1} exhibited recovery in the form of new shoots emerging from the root crown compared to plants treated with 58.8 g ai ha^{-1}, which suggests plant control improved as the florpyrauxifen-benzyl rate increased.

Outdoor mesocosm study

Based on greenhouse evaluations of parrotfeather watermilfoil sensitivity to florpyrauxifen-benzyl (all rates produced injury within 24 HAT and > 92% control 4 WAT), the outdoor mesocosm study included an additional lower herbicide dose (14.7 g ai ha^{-1}; half the previously tested low rate) to determine plant sensitivity to the new auxin herbicide. Similar to the greenhouse study, parrotfeather watermilfoil exhibited a more rapid response to florpyrauxifen-benzyl than did alligatorweed (Table 2). Within 48 HAT, parrotfeather watermilfoil displayed apical epinasty and plant canopy collapse among all treated mesocosms. Plants treated with florpyrauxifen-benzyl at 44.1 or 58.8 g ai ha^{-1}, reached complete necrosis by 2 WAT. Following the 2 WAT evaluation, visual control estimates remained > 96%, with all florpyrauxifen-benzyl rates providing > 99% control 8 WAT (Table 2). All herbicide rates reduced parrotfeather watermilfoil shoot and root biomass (Figure 2). However, signs of recovery were present for plants treated with the 14.7 g ai ha^{-1} rate, with minor regrowth of submersed plant tissue discovered at the sediment interface during harvest (8 WAT). Wersal and Madsen (2010) described similar parrotfeather watermilfoil regrowth forming at the root crowns following a foliar application of the auxin herbicide triclopyr (6.7 kg ae ha^{-1}). A potential sublethal response among florpyrauxifen-benzyl 14.7 g ai ha^{-1} treatments in this study should be further evaluated to determine if recovery of treated parrotfeather watermilfoil may occur with longer study periods (e.g., > 12 wk) to evaluate control longevity.

Initial injury observations of alligatorweed under outdoor mesocosm settings corresponded to the early findings of plant sensitivity to florpyrauxifen-benzyl with the greenhouse experiments. Signs of herbicide injury such as leaf hyponasty first appeared on plants treated with the 58.8 g ai ha^{-1} rate by 48 HAT, and all treatments experienced varying levels of chlorosis 5 DAT (leaf chlorosis increasing with florpyrauxifen-benzyl dose). Visual estimates of control peaked 4 WAT across all rates, with 44.1 and 58.8 g ai ha^{-1} providing > 90% control. Alligatorweed began to recover 5 to 6 WAT, with plants showing signs of recovery typical of auxin herbicide injury (e.g., thin and elongated leaves, swollen nodes, cupped leaves, and witches' broom). Plants that received a single herbicide application, regardless of original rate, were controlled < 18% based on visual control 12 WAIT, whereas repeat applications of florpyrauxifen-benzyl at 29.4, 44.1, and 58.8 g ai ha^{-1} provided > 94% control 12 WAIT. At harvest, all treatments reduced shoot biomass regardless of rate ($P < 0.001$; Figure 3). Although repeat applications of florpyrauxifen-benzyl at 29.4, 44.1, and 58.8 g ai ha^{-1} further reduced biomass, there were no significant differences among initial and repeat applications ($P > 0.05$). However, the 58.8 g ai ha^{-1} treatments (initial and repeat) were the most effective at reducing alligatorweed shoot biomass 12 WAIT (81.8 and 77.6%, respectively). Conversely, single and repeat florpyrauxifen-benzyl 14.7 g ai ha^{-1} treatments failed to provide acceptable plant control, as biomass increased over the study period (Figure 3).

Previous studies from the United States and New Zealand demonstrated that the auxin herbicides 2,4-D and triclopyr effectively controlled parrotfeather watermilfoil in small-scale mesocosm and field settings (Hofstra et al. 2006, Gray et al. 2007, Wersal and Madsen 2010). However, foliar applications of 2,4-D and triclopyr have resulted in variable alligatorweed control. One mesocosm study found foliar applied 2,4-D (1.06 and 2.13 kg ae ha^{-1}) and triclopyr (3.36 and 6.72 kg ae ha^{-1}) effectively reduced alligatorweed biomass (91 to 94 and 95%; 2,4-D and triclopyr, respectively) 12 WAT (Cox et al., 2014). Similarly, triclopyr (3.2 to 13.0 kg ae ha^{-1}) reduced alligatorweed biomass on recently established plants in a mesocosm experiment; however, a repeat application was necessary to maintain effective control when plants were more mature and had been established 8 MAT (Hofstra and Champion 2010). Likewise, a single foliar application of 2,4-D provided 80% alligatorweed control 2 WAT when sprayed in a shallow drainage canal in North Carolina with a 0.46–g ae 100 L^{-1} solution, but did not provide control 8 WAT (Langland 1986).

Although both parrotfeather watermilfoil and alligatorweed exhibit sensitivity to auxin herbicides, poor herbicide translocation from foliar applied herbicides likely contrib-

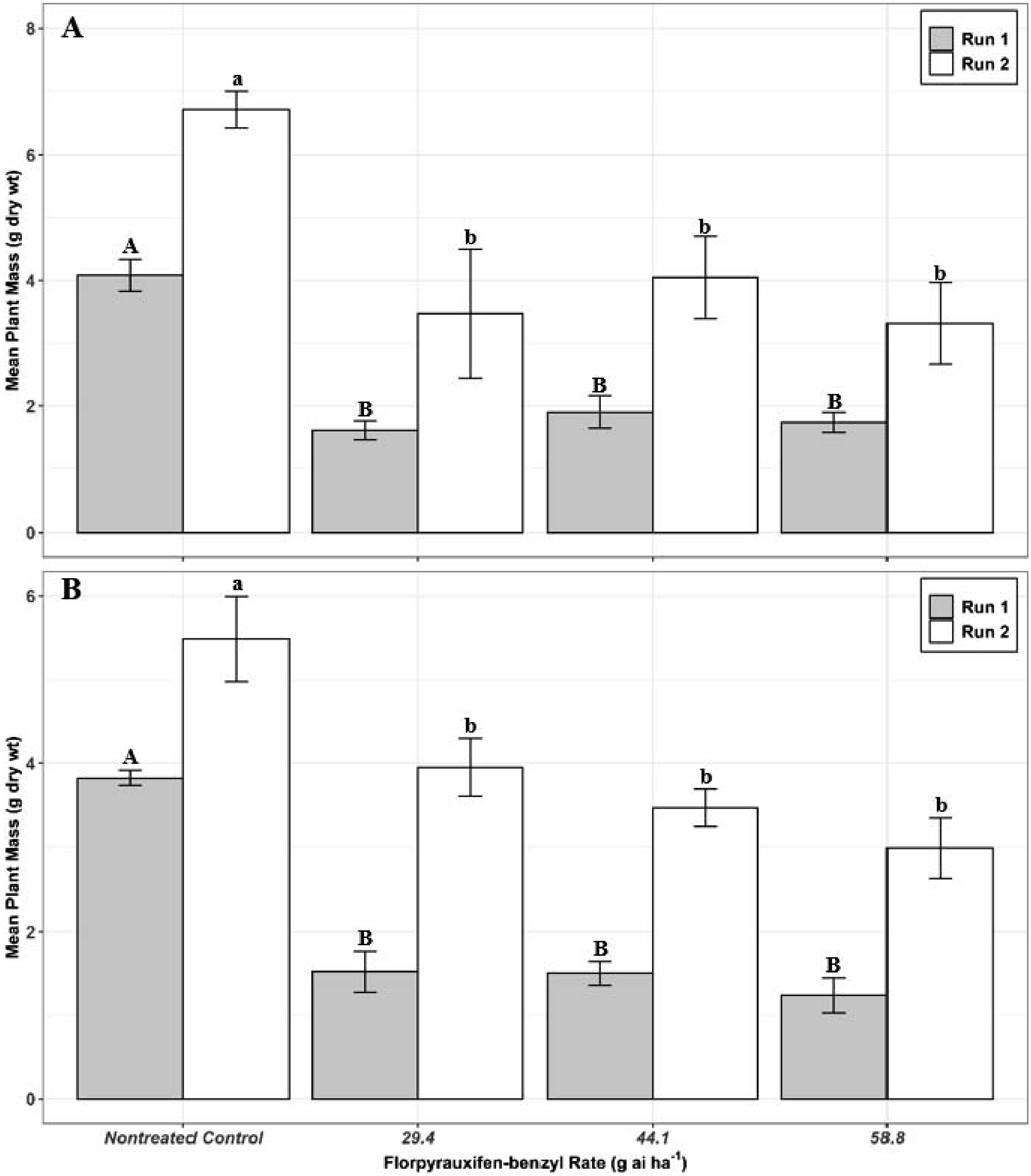

Figure 1. North Carolina greenhouse study response of (A) parrotfeather watermilfoil and (B) alligatorweed 4 wk after treatment with florpyrauxifen-benzyl. Graphs show dry weights (mean g dry weight ± SE). Treatments within runs that share the same letter are not different using Fisher's LSD at $P < 0.05$ significance level ($n = 4$).

Table 2. Visual estimates of parrotfeather watermilfoil and alligatorweed control following foliar applications of florpyrauxifen-benzyl in the New Zealand outdoor mesocosm study.

Treatment Rate (g ai ha^{-1})[1]	Parrotfeather (%)[2,4] 2 WAT[3]	4 WAT	8 WAT	Alligatorweed (%) 2 WAT	4 WAT	8 WAT	12 WAIT
14.7 (single)	96.3 a	98.7 a	99.2 a	47.5 a	56.3 a	5.5 a	0.0 a
29.4 (single)	99.7 a	99.9 b	99.7 a	77.5 b	85.4 b	49.5 b	2.0 a
44.1 (single)	100.0 a	99.9 b	100.0 a	78.3 b	90.7 b	62.4 bc	10.0 ab
58.8 (single)	100.0 a	100.0 b	100.0 a	85.4 b	93.8 b	68.3 c	18.0 b
14.7 (repeat)	–	–	–	–	–	–	55.0 c
29.4 (repeat)	–	–	–	–	–	–	94.0 d
44.1 (repeat)	–	–	–	–	–	–	95.6 d
58.8 (repeat)	–	–	–	–	–	–	98.2 d
Nontreated control	0.0 b	0.0 c	0.0 b	0.0 c	0.0 c	0.0 a	0.0 a

[1]All treatments included the addition of esterified seed oil (ESO) at 0.5% v/v in the spray solution.
[2]WAT: weeks after treatment; WAIT: weeks after initial treatment (4 wk after repeat applications for select alligatorweed bins).
[3]Control ratings based on visual estimates 0% (no injury) to 100% (complete desiccation).
[4]Means within columns followed by the same letter do not differ according to Fisher's Protected LSD ($P < 0.05$, $n = 10$).

utes to reduced alligatorweed control longevity (Dugdale and Champion 2012). Haug et al. (2021) evaluated the absorption rates of several submersed plant species and discovered Eurasian watermilfoil (*Myriophyllum spicatum* L.), hybrid watermilfoil (*Myriophyllum spicatum* L. × *Myriophyllum sibiricum* Komarov), and variable watermilfoil (*Myriophyllum heterophyllum* Michx.) treated with radiolabeled florpyrauxifen-benzyl at 10 µg ai L^{-1} had rapid active ingredient uptake in the plant shoots. Likewise, a similar ^{14}C study discovered basipetal translocation of the auxin herbicide, 2,4-D, when applied to mature emergent parrotfeather watermilfoil foliage (Sutton and Bingham 1970). In a small-scale CET study, Mudge et al. (2021) noted Eurasian watermilfoil was completely controlled 5 WAT following subsurface florpyrauxifen-benzyl applications of 3–, 6–, or 9–µg ai L^{-1} at 0.5-, 1-, or 3-h exposure times. Although not

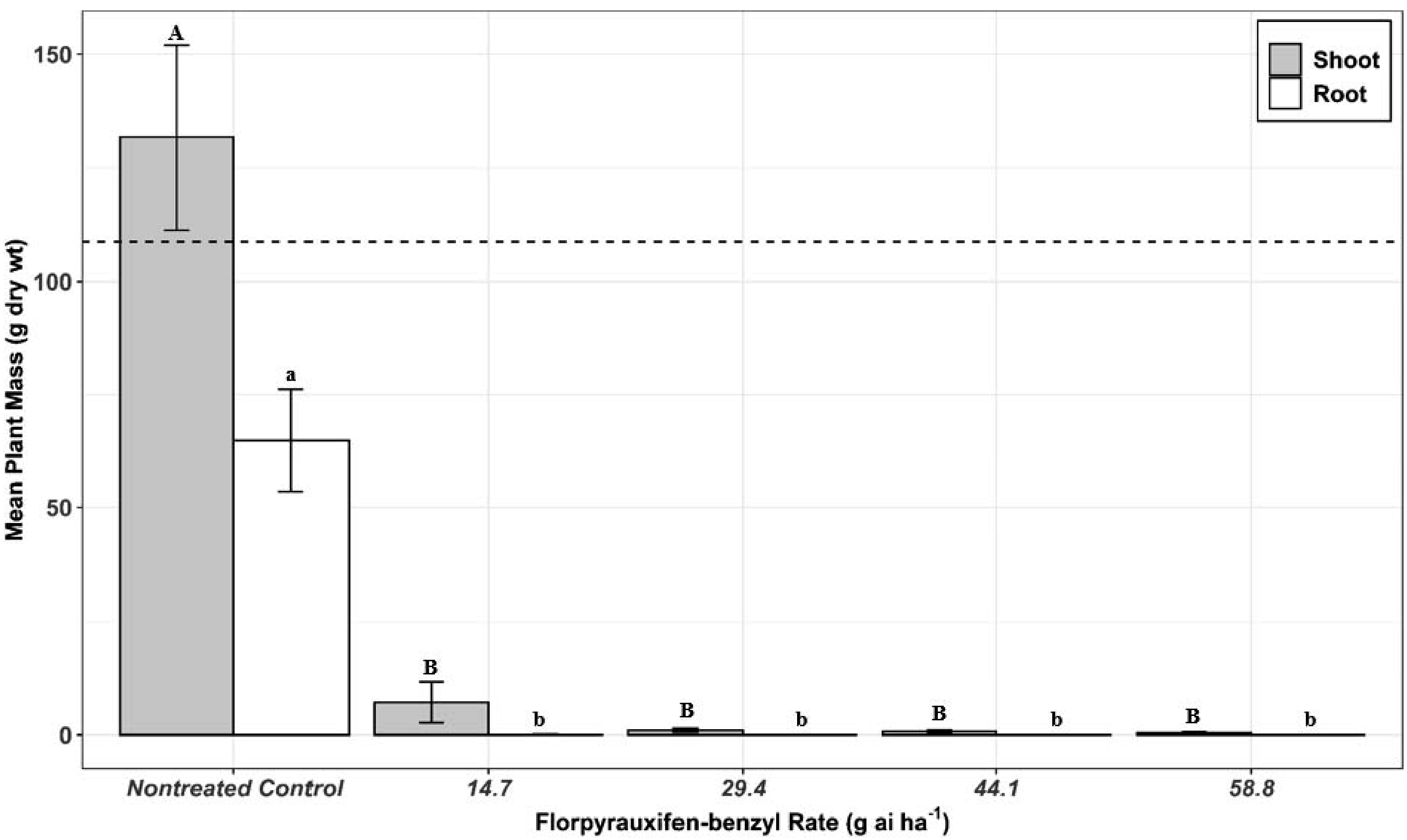

Figure 2. Response of parrotfeather watermilfoil shoot and root dry weights (mean g dry weight ± SE) to foliar-applied florpyrauxifen-benzyl at 8 wk after treatment in outdoor mesocosms in New Zealand. Treatments that share the same letter are not different using Fisher's LSD at $P < 0.05$ significance level ($n = 10$). The horizontal dash line represents mean pretreatment shoot biomass. All parrotfeather watermilfoil nontreated control plants actively grew over the study duration compared to the pretreatment reference (nontreated foliar biomass increased 20.9%).

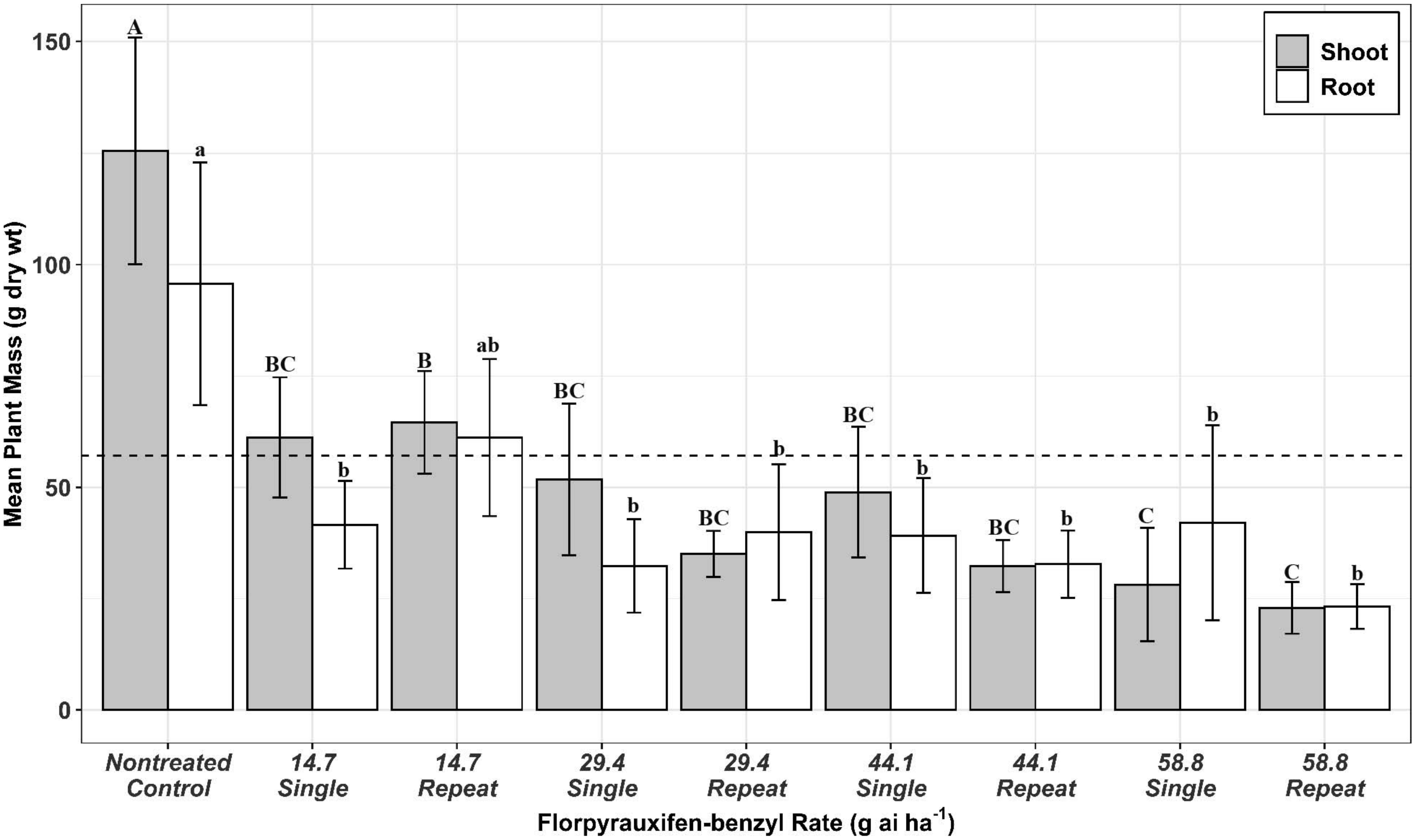

Figure 3. Response of alligatorweed shoot and root dry weights (mean g dry weight ± SE) to foliar-applied florpyrauxifen-benzyl at 12 wk after treatment in outdoor mesocosms in New Zealand. Treatments that share the same letter are not different using Fisher's LSD at $P < 0.05$ significance level ($n = 10$). The horizontal dash line represents mean pretreatment shoot biomass. All alligatorweed nontreated control plants actively grew over the study duration compared to the pretreatment reference (nontreated foliar biomass increased 67.6%).

directly comparable, these past studies further corroborate our findings where parrotfeather watermilfoil, as a *Myriophyllum* sp., displayed greater sensitivity to foliar applied florpyrauxifen-benzyl than observed for alligatorweed. Richardson et al. (2016) noted florpyrauxifen-benzyl in-water activity for submersed alligatorweed in small mesocosms had greater control (EC_{50} of 0.96 to 1.8 μg L^{-1}) than commonly expected among 2,4-D or triclopyr applications. Because absorption and translocation of foliar-applied herbicides like glyphosate and imazapyr have very limited activity in water (Bowmer et al. 1993, Tucker et al. 1994, Wersal and Madsen 2007), plants partially submersed in standing water would likely have even less control compared to plant targets having completely exposed biomass. It is unknown if alligatorweed foliar application studies from New Zealand trials experienced reduced efficacy having 10 to 20% of the basal portions of the plants submersed. In contrast to glyphosate and imazapyr however, florpyrauxifen-benzyl does show some in-water activity on alligatorweed (Richardson et al. 2016); thus, foliar herbicide spray not retained on the plant foliage may have accumulated in the ~10 cm of standing water and become available for plant absorption. Future studies should determine florpyrauxifen-benzyl absorption and metabolism in alligatorweed, and foliar plus in-water application techniques to evaluate the translocation of the florpyrauxifen-benzyl molecule when applied to submersed and foliar plant material.

In conclusion, this small-scale research demonstrates florpyrauxifen-benzyl has potential for parrotfeather watermilfoil control, with similar use patterns to other auxin herbicides for alligatorweed management. Results from both greenhouse and outdoor mesocosm studies indicate florpyrauxifen-benzyl has value in controlling parrotfeather watermilfoil with > 90% control 4 and 8 WAT, at rates ≥ 29.4 g ai ha^{-1}. Applying the lowest rate (14.7 g ai ha^{-1}) evaluated in this study under operational conditions would likely result in survival for both parrotfeather watermilfoil and alligatorweed. This application rate could also select for herbicide-resistant biotypes within a population (Richardson 2008), and is strongly discouraged. Although there was no difference in alligatorweed biomass reduction between florpyrauxifen-benzyl applied at 29.4 to 58.8–g ai ha^{-1} single or repeat applications, a repeat application would be necessary to achieve > 90% alligatorweed control 12 WAT based on results of these studies. Currently, repeat applications are common practice for long-term alligatorweed management and eradication programs (Hofstra and Champion, 2010).

Florpyrauxifen-benzyl is registered in the United States, and early operational use of the herbicide has shown favorable outcomes for controlling parrotfeather watermilfoil and alligatorweed (S. N. Sardes, pers. comm.). If approved in the country in the future, florpyrauxifen-benzyl may broaden the current herbicide portfolio in New Zealand where aquatic herbicide selection is limited. Future work should evaluate selectivity of this herbicide against potentially sensitive shoreline species (e.g., *Polygonaceae* spp.) so that use patterns do not negatively affect nontarget plant communities. Operational implementation of florpyrauxifen-benzyl in field settings should designate seasonal herbicide use patterns for parrotfeather watermilfoil and alligatorweed management (e.g., application timing and plant establishment), potential differences in plant control between product formulations (EC vs. SC), and the appropriate contact times needed for effective control (e.g., concentration and exposure trials simulating fetch wash). Water resource managers would additionally benefit from foliar combination studies with additional herbicide modes of action to screen potential tank mix partners for improving control longevity for alligatorweed and resistance management.

SOURCES OF MATERIALS

[1]Fafard® 2 Mix potting media, Conrad Fafard, Inc., P.O. Box 790, Agawam, MA 01001.

[2]Osmocote® fertilizer, The Scotts Company, 14111 Scottslawn Road, Marysville, OH 43040.

[3]ProcellaCOR EC, SePRO Corporation, Carmel, IN 46032.

[4]Teejet® XR8003 flat-fan nozzle, TeeJet Technologies, P.O. Box 832, Tifton, GA 31794.

[5]Hasten™ ESO Spray Adjuvant, BASF New Zealand Limited, P.O. Box 407, Auckland 1140.

[6]R version 4.0.3, R Foundation for Statistical Computing, Vienna, Austria.

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