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Efficacy of aquatic herbicides on dwarf rotala (*Rotala rotundifolia*)

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ABSTRACT

Rotala is an invasive aquatic plant that was introduced to the United States through the aquarium and water garden industries. The species has become a significant weed problem in southern Florida and is particularly troublesome in flood-control canals, where its dense growth impedes water movement. Previous research revealed that the organo-auxin herbicides 2,4-D and triclopyr provided good control of rotala, but the use of these products in canal systems can be problematic because of the risk of damage to nontarget species, such as crop and ornamental plants. Therefore, broad screening trials of aquatic herbicides on rotala were used to identify products that reduced biomass by 50% compared with untreated controls. Expanded testing was then conducted to determine the EC_{90} values—the concentration of herbicide required to reduce biomass by 90% compared with untreated controls. Most herbicides had EC_{90} values that were above the maximum label rate, but three may have utility for controlling rotala in aquatic systems. Foliar applications of bispyribac or imazamox at 44 or 469 g ai ha^{-1}, respectively, and submersed applications of fluridone at 37 µg ai L^{-1} reduced biomass of rotala by 90% compared with untreated controls. These EC_{90} values are less than half the maximum application rate allowed on the product labels. This research demonstrates that bispyribac, imazamox, and fluridone may be useful in rotation programs and/or as alternatives to the organo-auxins.

Key words: amphibious weeds, canal management, foliar application, herbicide screening.

INTRODUCTION

Florida's aquatic systems are constantly challenged by the introduction of nonnative species, many of which become invasive. The highest elevation in Florida is 60 m, but coastal regions and most of southern Florida are < 10 m above sea level (NASA 2004), so flood-control canals are an integral component of south Florida's rural/urban landscape. These channels must be kept clear of aquatic vegetation to ensure the rapid and reliable movement of water to protect people and property during periods of heavy rainfall. Several submersed aquatic weeds have invaded flood-control canals, which can drastically lower the volume of water that can be moved through these systems. One of the most recent invaders is dwarf rotala [*Rotala rotundifolia* (Buch.-Ham. ex Roxb.) Koehne], which forms dense monocultures that greatly reduce ecosystem services because oxygen production and light penetration are hampered (Gettys and Della Torre 2014). Importantly, water flow is restricted because of the excessive growth of this weed, so the ability of infested canals to function properly in flood-control systems is hindered. As such, management of this aquatic invader is a major concern.

Rotala was first discovered in Broward County in 1996 and has since established large, but mostly isolated, populations throughout the southern regions of Florida (Jacono and Vandiver 2007). It has red stems, bright green leaves, and spikes of fuchsia flowers (Gettys and Della Torre 2014). Rotala is easy to cultivate and grows well as either an emergent or submersed plant. Rotala generally establishes in the moist soils along the shoreline, then readily moves down into the water, where its growth rapidly fills the water column (C. J. Della Torre and L. A. Gettys, pers. obs.).

The genus *Rotala* comprises about 40 species, three of which are present in the United States. Lowland rotala [*Rotala ramosior* (L.) Koehne] is a native herb that is broadly distributed throughout the county and is considered endangered or threatened in New England and Washington State (USDA NRCS 2016b). A quick Internet search revealed that the introduced species Indian toothcup [*Rotala indica* (Willd.) Koehne and dwarf rotala (sometimes called roundleaf toothcup; hereafter, "rotala") are referred to interchangeably and synonymously by many aquarium plant dealers, but the U.S. Department of Agriculture (USDA) classifies them as distinct species with geographically discrete invasion patterns in the United States (USDA NRCS 2016a,c). Indian toothcup has been reported in California and Louisiana, whereas rotala has been introduced to Florida and Alabama (USDA NRCS 2016a,c).

Mechanical harvesting is the primary method currently used to manage rotala in flood-control canals, but that can be impractical for several reasons. Firstly, equipment expense and transport of harvested material can be cost prohibitive, and many sites are too remote for proper offloading of the harvested material. Secondly, mechanical harvesting can provide short-term results because regrowth from roots often occurs. In addition, the harvesting process often causes plant fragmentation; fragments are transport-

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ed downstream and often root at previously uninfested areas. Based on these limitations, alternatives to mechanical control are required.

Puri and Haller (2010) reported that endothall and flumioxazin did not cause measurable damage to rotala, whereas diquat (at 400 μg ai L^{-1}) provided about 80% control. Puri and Haller also found that submersed applications of triclopyr or 2,4-D at 2 mg L^{-1} could be expected to result in total or near-total control of rotala. Unfortunately, both of these herbicides are organo-auxins, which are known to cause significant damage at low concentrations to sensitive species, such as crop and ornamental plants. Although products with 2,4-D as the active ingredient have irrigation restrictions that are as short as 7 d, most herbicide labels for products containing triclopyr require that treated water not be used for crop irrigation for 120 d after the application or until herbicide concentrations are < 1 ppbv.

Herbicide resistance or tolerance in the genus *Rotala* is not unknown because the phenomenon was first documented in a biotype of Indian toothcup in Asia in 1997 (Uchino et al 2016). That biotype was resistant to the acetolactate synthase (ALS)-inhibiting sulfonylurea (SU) herbicides bensulfuron methyl, pyrazosulfuron ethyl, and imazosulfuron (Blancaver et al. 2001). Further testing revealed that the biotype was cross-resistant to a number of other SU herbicides as well (Kuk et al. 2002). Blancaver et al. (2002) evaluated whole-plant response of SU-resistant and SU-susceptible biotypes of Indian toothcup to the non-SU ALS-inhibiting herbicides bispyribac sodium (pyrimidinyl-carboxy [PC]) and imazamox (imidazolinone [IM]) and found that SU resistance status had no measurable impact on resistance to the PC or IM herbicides tested. Both biotypes were susceptible to bispyribac sodium at a rate lower than that recommended (200 g ai ha^{-1}) for weed control in direct-seeded rice fields and resistant to imazamox at higher than the recommended rate (17 g ai ha^{-1}) for weed control in adzuki bean [*Vigna angularis* (Willd.) Ohwi & H. Ohashi] fields (Blancaver et al. 2002).

Puri and Haller (2010) suggested that of the five aquatic herbicides evaluated (diquat, endothall, flumioxazin, triclopyr, and 2,4-D), only the organo-auxins provided $> 90\%$ control of rotala. Additional herbicide efficacy evaluations are merited for several reasons. For example, a number of other herbicides are labeled for aquatic use in the United States, including bispyribac, carfentrazone, fluridone, glyphosate, imazamox, penoxsulam, and topramezone, but the activity of those products on rotala is unknown. In addition, many flood control canals are bordered by development, including residential and commercial operations, such as landscape nurseries, so the use of organo-auxins in those systems should be avoided if possible to reduce the risk of nontarget damage from drift and irrigation with herbicide-treated water. Therefore, the objectives of these experiments were to confirm previous findings that organo-auxins provide good control of rotala, which could be useful in waters that are not used for irrigation, and to evaluate herbicides labeled for aquatic use to determine efficacy on rotala.

MATERIALS AND METHODS

Rotala plant material was collected as needed during 2013 and 2014 from existing stocks in Davie, FL, and Gainesville, FL. Apical tip cuttings (10 cm long) were collected and planted 10 pot^{-1} in 2-L pots without holes, which were filled with coarse builder's sand amended with 5 g pot^{-1} of a controlled-release fertilizer.[1] Rotala cultures were initiated in unheated greenhouses under terrestrial/shallow water conditions and transferred to submersed conditions when new growth was evident. Once established, plants were selected for uniformity and randomly moved into mesocosms (46 cm in diameter by 46 cm deep; total volume 77.6 L), filled with 65 L of well water to begin herbicide testing. Three replicates (mesocosms) were prepared for each treatment in all experiments. Water levels were maintained at 38 cm throughout the course of the experiments. Initial screening trials were conducted separately on emergent and submersed rotala using foliar (emergent) or water column (submersed) applications to identify which products merited further evaluation. All herbicides that were evaluated in the initial screening trials were tested at maximum and half-maximum label rates and concentrations (Table 1), and all herbicides used for foliar (emergent) testing included a nonionic surfactant[2] at a concentration of 0.25%.

Foliar application trials

Herbicides (Table 1) were applied to emergent rotala (mesocosm coverage $> 90\%$) using aerosol spray units[3] fitted with 50-ml glass jars. Each suction straw and spray nozzle was used to apply a single herbicide, then replaced with a new straw and nozzle before applying the next treatment to minimize contamination. The surface area of each mesocosm was 1,688 cm^2, and an application rate of 935 L ha^{-1} (16 ml solution $mesocosm^{-1}$) was used to ensure adequate coverage of all emergent plant material in each mesocosm. Treatments and untreated controls (applications of water and surfactant only) were arranged in a randomized complete-block design. Each mesocosm was treated once on 18 December 2013. Plants were maintained under static conditions and were destructively harvested during the week of 14 March 2014 (3 mo after treatment [MAT]). All live, aboveground plant material was cleaned of debris, dried in a forced-air oven at 65 C for 1 wk and weighed to determine aboveground biomass per replicate. Data were analyzed in SAS software,[4] version 9.3, using ANOVA, and means were separated using Fisher's Protected LSD test ($P = 0.05$).

Submersed application trials

Well-established submersed cultures of rotala were transferred to mesocosms 2 mo after planting and were allowed to grow for an additional 3 wk before treatment. The volume of water in each mesocosm was 65 L, and a total volume of 200 ml of each herbicide/diluent mix was applied to each mesocosm (Table 1). Treatments and untreated controls (addition of 200 ml of water only) were arranged in a randomized complete-block design. Each mesocosm was

Table 1. Herbicides evaluated in initial screening trials for efficacy on rotala. Rates represent the maximum and half-maximum application rates listed on the label of each product. All foliar treatments included a nonionic surfactant.

Active ingredient	Foliar Rates (g ha^{-1})[1]	Submersed Rates (ppbv)[2]
2,4-D	—[3]; 2,128	—; 4,000
Aminopyralid	61; 122	—
Bispyribac	56; 112	22.5; 45
Carfentrazone	89; 177	100; 200
Diquat	—	—; 368
Endothall	—	2,500; 5,000
Flumioxazin	214; 428	200; 400
Fluridone	135; 270[4]	45; 90
Glyphosate	2,100; 4,199	—
Imazamox	560; 1,120	250; 500
Penoxsulam	49; 98	75; 150
Topramezone	196; 392	25; 50
Triclopyr	—; 720	—; 2,500

[1]Grams of acid equivalent used for auxins and glyphosate; active ingredient per hectare used for other herbicides.
[2]Micrograms of acid equivalent used for auxins and cation (diquat); active ingredient per liter used for other herbicides.
[3]A dash (—) indicates that a rate was not tested.
[4]There are no label instructions for foliar applications of fluridone; evaluations were made on the equivalent of a theoretical maximum label concentration of 270 g ai ha^{-1}, which would result in a concentration of 90 ppbv of fluridone in a water-column treatment.

treated once in late March 2014, and plants were maintained under static conditions for 3 MAT, when plant material was processed, and data were analyzed using the methods described above for foliar treatments.

Expanded EC_{90} experiments

Herbicides that reduced biomass by > 50% in the initial screening trials were subjected to additional trials with a wider range of application rates—from 1/16th to 2 times the maximum label rate (Table 2)—to determine EC_{90} values (the concentration required to reduce biomass by 90% compared with untreated control plants). These trials were established and treated as described for the screening trials. Foliar treatments were applied to emergent rotala on 17 April 2014 in Gainesville, and plants were harvested on 17 July 2014. Water column treatments were performed on submersed rotala on 16 June 2014 in Davie, and plants were harvested on 10 September 2014. Dry biomass data were subjected to ANOVA, and regression was performed using exponential decay function.

Table 2. Herbicides evaluated in expanded concentration of herbicide required to reduce biomass by 90% (EC_{90}) trials. Maximum label rate is indicated by bold, underlined type.

Active ingredient	Foliar Rates (g ai ha^{-1})	Submersed Rates (µg ai L^{-1})
Bispyribac	7, 14, 28, 56, **<u>112</u>**, 224	2.8, 5.5, 11, 23, **<u>45</u>**, 90
Endothall	—	313, 625, 1,250, 2,500, **<u>5,000</u>**, 10,000
Fluridone[1]	17, 34, 68, 135, **<u>270</u>**, 540	5.6, 11, 23, 45, **<u>90</u>**, 180
Imazamox	70, 140, 280, 560, **<u>1,120</u>**, 2,240	31, 63, 125, 250, **<u>500</u>**, 1,000
Penoxsulam	6, 12, 25, 49, **<u>98</u>**, 196	9, 19, 38, 75, **<u>150</u>**, 300
Topramezone	25, 49, 98, 196, **<u>392</u>**, 784	3.1, 6.3, 12.5, 25, **<u>50</u>**, 100

[1]There are no label instructions for foliar applications of fluridone; evaluations were made on the equivalent of a theoretical maximum label concentration of 270 g ai ha^{-1}, which would result in a concentration of 90 ppbv of fluridone in a water column treatment.

Table 3. Percentage of reduction in dry biomass of emergent rotala in initial screening trials. Plants were treated once with a foliar application of a single herbicide and maintained under static conditions for 3 mo after treatment. Values represent the percentage of reduction in dry biomass of three replicates per treatment as compared with untreated controls.

Herbicide	Rate[1]	% Biomass Reduction (g)
2,4-D	350 g ae ha^{-1}	Not tested
	175 g ae ha^{-1}	90.4
Aminopyralid	20.1 g ae ha^{-1}	99.5
	10.1 g ae ha^{-1}	85.2
Bispyribac	18 g ai ha^{-1}	59.2
	9 g ai ha^{-1}	38.3
Carfentrazone	29 g ai ha^{-1}	34.0
	14.5 g ai ha^{-1}	13.0
Flumioxazin	70 g ai ha^{-1}	69.0
	35 g ai ha^{-1}	75.1
Fluridone	44 g ai ha^{-1}	70.1
	22 g ai ha^{-1}	59.1
Glyphosate	689 g ae ha^{-1}	42.3
	344 g ae ha^{-1}	3.4
Imazamox	184 g ai ha^{-1}	77.0
	92 g ai ha^{-1}	68.7
Penoxsulam	16 g ai ha^{-1}	54.3
	8 g ai ha^{-1}	18.2
Topramezone	64 g ai ha^{-1}	76.9
	32 g ai ha^{-1}	23.6
Triclopyr	1,102 g ae ha^{-1}	Not tested
	551 g ae ha^{-1}	100

[1]Application rates correspond to the maximum (upper) and half-maximum (lower) rate on the product label.

RESULTS AND DISCUSSION

Foliar treatments—Initial screening trials

Analysis of dry weight data for plant materials harvested 3 MAT revealed that foliar applications of the auxins 2,4-D, triclopyr, and aminopyralid resulted in 91 to 100% control (Table 3). The nonauxin herbicides (bispyribac, flumioxazin, fluridone, imazamox, penoxsulam, and topramezone), when applied at their maximum foliar rate, reduced biomass by ≥ 50% compared with untreated control plants. Because one of the objectives of these experiments was to identify herbicides other than the auxins that could effectively control rotala, the auxins were not advanced to the expanded EC_{90} screening trial. In addition, although flumioxazin performed well in the screening trial, it was not advanced for further study because reports regarding this herbicide's performance in the field are inconsistent. For example, a number of resource managers have suggested that flumioxazin at 214 g ai ha^{-1} (half the maximum label rate) provided good control of rotala, but others have not had the same level of success (M. Bodle, pers. comm.; S. Montgomery, pers. comm.; and others). In addition, we conducted a small field trial with flumioxazin and diquat in a rotala-infested pond on site at the Fort Lauderdale Research and Education Center (Davie, FL). The pond was treated twice—one emergent (foliar) application (428 g ai ha^{-1} flumioxazin plus 2,242 g ai ha^{-1} diquat),

Table 4. Concentration values of herbicide required to reduce biomass by 90% (EC_{90}), regression equations, and 95% confidence intervals (95% CI) of herbicides applied as foliar treatments to emergent rotala in expanded trials in Gainesville, FL. Maximum label rate for each herbicide is indicated by bold, underlined type.

Herbicide	Maximum Label Rate[1]	EC_{90}[1]	95% CI[1]	Regression Equation	r^2
Bispyribac	112	44	24–101	$y = 137.2\ \exp(-0.052x)$	0.917
Fluridone[3]	270	316	235–481	$y = 145.6\ \exp(-0.00729x)$	0.901
Imazamox	1,120	469	288–1,272	$y = 124.1\ \exp(-0.00491x)$	0.879
Penoxsulam	98	*[2]	Not applicable	$y = 126.3\ \exp\ (-0.0428x)$	0.788
Topramezone	392	558	385–*	$y = 147.1\ \exp(-0.00413x)$	0.912

[1]Grams of active ingredient per hectare.
[2]An asterisk (*) means the result was higher than highest rate tested (two times maximum label rate).
[3]There are no label instructions for foliar applications of fluridone; evaluations were made on the equivalent of a theoretical maximum label concentration of 270 g ai ha^{-1}, which would result in a concentration of 90 ppb of fluridone in a water column treatment

followed 1 mo later by a submersed/subsurface application (400 μg ai L^{-1} flumioxazin plus 735 μg ai L^{-1} diquat). Although plants were initially injured by the applications, they ultimately recovered from the herbicide damage and have regrown into a population that is as robust as it was before treatment. These results, coupled with how rapidly flumioxazin degrades in high-pH water, suggest that this protoporphyrinogen oxidase inhibitor may have limited use for control of rotala.

Foliar treatments—Expanded EC_{90} trials

Bispyribac, fluridone, imazamox, penoxsulam, and topramezone were applied at the rates shown in Table 2 to foliage of emergent rotala, using the protocols described above. Of the five herbicides tested, only bispyribac and imazamox had EC_{90} values that were lower than their respective maximum-labeled rates (Table 4). The EC_{90} of bispyribac was 44 g ai ha^{-1} (maximum label rate, 112 g ai ha^{-1}) and the EC_{90} of imazamox was 469 g ai ha^{-1} (maximum label rate, 1,120 g ai ha^{-1}). These results suggest that foliar applications of bispyribac or imazamox at rates allowed on the product labels could provide acceptable control of emergent rotala. However, mesocosm studies are performed under controlled conditions, and small amounts of herbicide may have reached the water column, despite the dense, emergent growth of rotala treated in these studies. As a result, field applications may produce results that differ significantly from those described in this article and small-scale field trials should be performed before broad operational use of these herbicides to verify that the mesocosm findings translate well to the more-dynamic conditions present in natural systems.

One of the goals of these experiments was to identify herbicides with shorter irrigation restrictions than the organo-auxins, so an evaluation of the use restrictions on water treated with bispyribac and imazamox may be helpful to inform management decisions. The label for Tradewind,[5] which contains bispyribac and is approved for aquatic use, indicates that treated water cannot be used for irrigation of food or ornamental species until the concentration of bispyribac is < 1 ppbv as determined by enzyme-linked immunosorbent assay (ELISA) or other approved analytical methods (Anonymous 2011). Bispyribac is degraded via microbial action and generally has a long (30+ d) half-life, but several factors influence the rate of degradation (Netherland 2014) and published bispyribac half-life values range from as little as 2 d (Zanella et al. 2011 and references therein) to 42 d (Kanrar and Bhattacharyya 2010). The treatments described above were applied to dense, emergent vegetation (> 90% coverage); whereas it is possible that a little bispyribac reached the water column, it seems unlikely that the water-column concentrations would be high enough (i.e., > 1 μg ai L^{-1}) to trigger irrigation restrictions. The label for Clearcast,[6] which contains imazamox and is approved for aquatic use, lists a 24-h irrigation restriction for still or quiescent waters when the treatment area is > 25% of the total surface area or is < 33 m from an irrigation intake (Anonymous 2013). The label also indicates that there is no restriction on using flowing water for irrigation if < 560 g ai ha^{-1} of Clearcast is applied. Because the EC_{90} of imazamox on rotala was 469 g ai ha^{-1}, the maximum irrigation restriction that would be required under field conditions would be 1 d.

At first glance, these results seem to conflict with those reported by Blancaver et al. (2002), who reported "resistance" (which could actually be "tolerance") to imazamox and susceptibility to bispyribac in Indian toothcup; however, a number of factors (in addition to species differences) contribute to the differences. Blancaver et al. (2002) applied herbicides as a "top-dress" treatment to 3-cm-tall seedlings in flooded soil with ≥ 5 cm of water over the soil surface, whereas our products were applied to the emergent foliage of topped-out, mature plants. Recommended application rates differed as well; Blancover et al. tested bispyribac and imazamox at recommended rates of 200 and 17 g ai ha^{-1}, respectively, whereas our maximum label rates of these products were 112 and 1,120 g ai ha^{-1}, respectively. Susceptibility to bispyribac was common in both experiments, but Blancover et al. reported resistance (or tolerance) to imazamox, which was not unexpected, given that our calculated EC_{90} value for imazamox was 469 g ai ha^{-1}.

Water column treatments—Initial screening trials

Subsurface applications of diquat or the auxins resulted in 91 to 100% control of rotala 3 MAT (Table 5). The maximum label rates of bispyribac, carfentrazone, endothall, flumioxazin, fluridone, imazamox, penoxsulam, and topramezone reduced biomass by ≥ 50% compared with untreated control plants. Although carfentrazone produced better control as a water-column treatment compared with

Table 5. Percentage of reduction in dry biomass of submersed rotala in initial screening trials. Plants were treated once with a water-column application of a single herbicide and maintained under static conditions for 3 mo after treatment. Values represent the percentage of reduction in dry biomass of three replicates per treatment as compared with untreated controls.

Herbicide	Rate[1]	% Biomass Reduction (g)
2,4-D	3,972 µg ae L^{-1}	100
	1,986 µg ae L^{-1}	Not tested
Bispyribac	44 µg ai L^{-1}	87.1
	22 µg ai L^{-1}	77.5
Carfentrazone	158 µg ai L^{-1}	59.2
	79 µg ai L^{-1}	58.6
Diquat	184 µg ai cation L^{-1}	Not tested
	368 µg ai cation L^{-1}	100
Endothall	4,978 µg ai L^{-1}	65.0
	2,489 µg ai L^{-1}	59.9
Flumioxazin	394 µg ai L^{-1}	88.7
	193 µg ai L^{-1}	35.3
Fluridone	89 µg ai L^{-1}	91.5
	44 µg ai L^{-1}	53.6
Imazamox	497 µg ai L^{-1}	91.2
	249 µg ai L^{-1}	86.2
Penoxsulam	151 µg ai L^{-1}	59.7
	75 µg ai L^{-1}	80.9
Topramezone	50 µg ai L^{-1}	64.7
	25 µg ai L^{-1}	68.3
Triclopyr	2,537 µg ae L^{-1}	100
	1,269 µg ae L^{-1}	Not tested

[1]Application rates correspond to the maximum (upper) and half-maximum (lower) rate on the product label.

foliar applications (60% reduction in submersed trials vs. 35% reduction in foliar trials), it was not evaluated in the EC_{90} trials because of both its weak performance after foliar application and because carfentrazone, like flumioxazin, is rapidly degraded when applied to high-pH waters. The auxins and flumioxazin were not advanced to the expanded EC_{90} screening trial for the reasons described in the foliar section. Diquat was not subjected to further study because many of the canals infested by rotala are turbid and diquat rapidly binds to suspended particles in the water column. Therefore, submersed field applications of diquat may not be as successful as these experiments, which were performed in still, clear water in mesocosms.

Water column treatments—Expanded EC_{90} trials

Bispyribac, endothall, fluridone, imazamox, penoxsulam, and topramezone were applied at the rates shown in Table 2 to submersed rotala using the protocols described above. Of those six herbicides, only fluridone had an EC_{90} value that was lower than its maximum label rate (EC_{90} of 37 µg ai L^{-1} vs. maximum label rate of 90 µg ai L^{-1} in ponds [fluridone may be used at rates of up to 150 µg ai L^{-1} in lakes and reservoirs]) (Table 6). These results suggest that water-column applications of fluridone at concentrations allowed on the product label could provide good control of submersed rotala—particularly in systems with limited flow because the contact exposure time of fluridone can be 45 d or more—and merits field evaluation.

There were major differences noted between screening and expanded studies, indicating that seasonality may have had a role in those differences. Initial foliar screening trials were conducted in a greenhouse in Ft. Lauderdale, FL, at maximum and half-maximum label rates in winter/spring (December 2013 to March 2014). Those screening trials were followed by expanded tests in a greenhouse in Gainesville in spring/summer (April to July 2014). Submersed experiments were conducted under a similar timeline; initial screening trials were performed in spring (March to June 2014) in Gainesville and were followed by expanded tests in Ft. Lauderdale in summer (June to September 2014). Temperature differences between Gainesville and Fort Lauderdale, can be extreme, and that may have influenced the outcome of these experiments. For example, initial submersed screening trials conducted in Gainesville during spring revealed that 5,000 µg ai L^{-1} of endothall resulted in a 60% reduction in biomass. In contrast, the EC_{90} of endothall calculated after expanded trials during the summer in Fort Lauderdale was $> 10{,}000$ µg ai L^{-1}. These differences might be due to warmer water temperatures in the Fort Lauderdale summer trials, which would greatly shorten the half-life of endothall in the submersed treatments from microbial decomposition. Fluridone applied at the maximum label rate of 90 µg ai L^{-1} in initial screening trials in Gainesville during spring resulted in 95% reduction of rotala growth, but expanded trials performed in Fort Lauderdale during summer yielded an EC_{90} value of 37 µg ai L^{-1}. Fluridone is known to be more active on rapidly growing plants; plant growth in Fort Lauderdale during summer is much greater than growth in Gainesville in spring, which could explain these somewhat different results.

The results of these studies suggest that field trials should be conducted with foliar applications of the ALS inhibitors bispyribac and imazamox because both of these products had foliar EC_{90} values less than the maximum label rates. There are no restrictions on recreational use of waters

Table 6. Concentration values of herbicide required to reduce biomass by 90% (EC_{90}), regression equations, and 95% confidence intervals (95% CI) of herbicides applied as water-column treatments to submersed rotala in expanded EC_{90} trials in Davie, FL. Maximum label rate for each herbicide is indicated by bold, underlined type.

Herbicide	Maximum Label Rate[1]	EC_{90}[1,2]	95% CI[1,2]	Regression Equation	r^2
Bispyribac	45	*	*–*	$y = 67.1576 \exp(-0.00601x)$	0.764
Endothall	5,000	*	*–*	$y = 69.617 \exp(-0.002x)$	0.471
Fluridone	90	37	23–92	$y = 77.2526 \exp(-0.0617x)$	0.925
Imazamox	500	*	*–*	$y = 61.5079 \exp(-0.00085x)$	0.820
Penoxsulam	150	*	*–*	$y = 62.0663 \exp(-0.0013x)$	0.764
Topramezone	50	*	*–*	$y = 66.2924e \exp(-0.0053x)$	0.888

[1]In micrograms active ingredient per liter.
[2]Asterisk (*) indicates the result was higher than highest rate tested (two times the maximum label rate).

treated with bispyribac or imazamox; however, both herbicides have irrigation restrictions. Bispyribac-treated water must have a concentration of ≤ 1 µg ai L^{-1} as determined by ELISA or other approved analytical methods before it can be used for watering of livestock, food crops, and ornamental species (Valent 2011). The concentration of imazamox must be ≤ 1 µg ai L^{-1} before treated water can be used for irrigation of greenhouse, nursery, and hydroponic crops. Irrigation of other plants is allowed when the concentration of imazamox is ≤ 50 µg ai L^{-1} (SePRO 2013), which would allow use of the foliar EC_{90} rate found in these experiments without restriction in Florida canal systems that do not border greenhouse, nursery, and hydroponic production areas (469 g ai $ha^{-1} < 559$ g ai ha^{-1} that results in a concentration of 50 µg ai L^{-1} in canals 1.2 m deep). As such, the use of treated waters for irrigation could still be a major consideration with these two herbicides.

Although initial submersed tests showed that bispyribac, imazamox, and endothall had good activity during spring (March to June 2014), only fluridone treatments in summer had an EC_{90} value that was less than the maximum concentration allowed by the label (EC_{90} of 37 µg ai L^{-1} vs. maximum concentration of 90 µg ai L^{-1} in ponds and 150 µg ai L^{-1} in lakes and reservoirs). These data suggest that bispyribac and endothall may have good activity in early spring treatments and should be further evaluated, particularly because endothall has few irrigation restrictions. The use of fluridone and bispyribac in ponds may also be effective for control of rotala; however, not only do both have irrigation restrictions, both have relatively long concentration exposure time requirements of 45 d or greater (Netherland 2014), which may limit their use in flowing water conditions.

These experiments reveal that resource managers may have additional tools besides the organo-auxins to control rotala. Foliar applications of the ALS inhibitors bispyribac and imazamox provided good control of rotala in mesocosm studies and both had EC_{90} values that were less than half the maximum label rate; water column treatment with fluridone provided similar results. This research shows that bispyribac, imazamox and fluridone may be useful in rotation programs and/or as alternatives to the organo-auxins for control of rotala.

SOURCES OF MATERIALS

[1]Osmocote Plus 15–9–12 (N–P–L), Everris, 4950 Blazer Parkway, Dublin, OH 43017.

[2]LI-700, Loveland Products, 14520 County Road 64, Greeley, CO 80634.

[3]Preval Sprayer, Preval, 1300 E. North Street, Coal City, IL 60416.

[4]SAS software, version 9.3, SAS Institute, 100 SAS Campus Drive, Cary, NC 27513-2414.

[5]Tradewind, Valent, 1600 Riviera Avenue, Suite 200, Walnut Creek, CA 94596-8025.

[6]Clearcast, SePRO, 11550 North Meridian Street, Suite 600, Carmel, IN 46032.

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