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Brazilian egeria herbicide mesocosm and field trials for managing the Sacramento–San Joaquin River Delta

JOHN D. MADSEN, CHRISTY MORGAN, JOHN MISKELLA, GUY KYSER, PATRICIA GILBERT, JON O'BRIEN, AND KURT D. GETSINGER*

ABSTRACT

The nonnative Brazilian egeria (*Egeria densa* Planch.) is the dominant submersed plant in the Sacramento–San Joaquin River Delta, displacing native plant species and degrading habitat for endangered fish species. A mesocosm study was conducted at the U.S. Department of Agriculture (USDA) facility in Davis, CA to determine efficacy of aquatic herbicides on egeria. Fifty mesocosm tanks of 167 L capacity were planted with four 4.2-L pots of egeria. Four tanks each were treated with bispyribac sodium (45 μg L^{-1}), carfentrazone-ethyl (200 μg L^{-1}), ethylenediamine chelate of copper (1,000 μg L^{-1}), diquat (390 μg L^{-1}), dipotassium salt of endothall (5,000 μg L^{-1}), dimethylalkylamine salt of endothall (5,000 μg L^{-1}), florpyrauxifen-benzyl (50 μg L^{-1}), flumioxazin (400 μg L^{-1}), fluridone (60 μg L^{-1}), imazamox (500 μg L^{-1}), penoxsulam (60 μg L^{-1}), and four tanks were left as an untreated reference. All were single treatments, static exposures for 10 wk. At the end of 10 wk, all pots were harvested, and the shoots were dried at 70 C for 48 h. All herbicides produced some statistically significant reduction in biomass. Copper, diquat, endothall dimethylalkylamine, and fluridone produced > 90% control. Carfentrazone (69%) and the potassium salt of endothall (62%) provided greater than 50% control, with other herbicides producing somewhat less than 50% control. Field demonstration has substantiated some of these findings. A study of three treatment plots in 2016 found an 85% reduction in biomass in fluridone-treated plots, compared to a 26% increase in biomass in untreated plots. A field trial on two plots treated with diquat found 98% and 80% control, respectively. A field trial with the dipotassium salt of endothall resulted in 43% control after one treatment.

Key words: diquat, *Egeria densa* Planch., endothall, fluridone, freshwater tidal estuary.

*First author: Research Biologist, USDA ARS Invasive Species and Pollinator Health Research Unit, University of California–Davis, 1 Shield Avenue, Davis, CA 95616. Second, third, and fourth authors: Plant Sciences Department, 1 Shield Avenue, University of California–Davis, Davis, CA 95616. Fifth and sixth authors: California State Parks Division of Boating and Waterways, Sacramento, CA 94296. Seventh author: U.S. Army Engineer Research and Development Center, Environmental Laboratory, Vicksburg, MS 39180. Corresponding author's E-mail: jmadsen@ucdavis.edu. Received for publication August 31, 2019 and in revised form May 15, 2020.

INTRODUCTION

The Sacramento–San Joaquin River Delta (hereafter "Delta") is formed by the confluence of the Sacramento River from the north, and the San Joaquin River from the south. The Delta is the hub of water transport in California, from which water is pumped into the California Aqueduct to agricultural and domestic users to the south, as well as for users in the Delta (DSC 2013). The water irrigates 1.6M ha (4M acres) of farmland and provides domestic water to 25M users in California. The 27,500 ha (68,000 acre) waterway is habitat for 56 rare, threatened, and endangered species, and is used by fish and wildlife, as well as serving as a transportation corridor for 4M tons yr^{-1} of shipping and 2M recreational boating trips yr^{-1} (DSC 2013).

Water uses can be obstructed by the growth of over a dozen invasive aquatic plant species; the primary submersed nuisance plant is Brazilian egeria (*Egeria densa* Planch.), with some estimates of as much as 8,000 ha (20,000 acres) in the Delta (Ta et al. 2017). Other invasive aquatic plants in the Delta include the emergent plants alligatorweed [*Alternanthera philoxeroides* (Mart.) Griseb.], giant reed (*Arundo donax* L.), and waterprimrose (*Ludwigia* spp.); free-floating plants spongeplant (*Limnobium laevigatum* (Humb. & Bonpl. ex. Willd.) Heine) and waterhyacinth [*Eichhornia crassipes* (Mart.) Solms]; and submersed plants coontail (*Ceratophyllum demersum* L.), fanwort (*Cabomba caroliniana* A. Gray), Eurasian watermilfoil (*Myriophyllum spicatum* L.), and curlyleaf pondweed (*Potamogeton crispus* L.).

Egeria is an evergreen perennial submersed plant that is originally from the subtropical regions of Brazil, Argentina, and Uruguay (Cook and Urmi-Konig 1984, Yarrow et al. 2009). It has spread to other regions of South America, North America, Europe, Africa, Japan, Australia, and New Zealand (Cook and Urmi-Konig 1984). Egeria is found in water bodies from New England south to Florida, across the southern and middle tier of states in the Midwest and Plains, the Southwest, and on the west coast from California to Washington. Egeria is only found in British Columbia of the Canadian provinces (USDA NRCS 2019, USGS 2019). Egeria forms a dense canopy through prolific branching close to the surface (Getsinger and Dillon 1984). In South Carolina, egeria reached a peak biomass in September and senesced to a reduced biomass before quiescence (Getsinger and Dillon 1984). Egeria populations in Japan likewise have green shoot material present throughout the year (Haramoto and Ikusima 1988). Egeria reproduces and spreads through stem fragments, runnering (stems forming new rooting attachments), and double node production (Haramoto and Ikusima 1988). Egeria is dioecious, forming showy staminate flowers at the surface. In North America, however, the only plants present form staminate flowers, so no seeds are produced (USGS 2019). Egeria has been identified to have numerous adverse impacts to aquatic systems, including outcompeting native vegetation, reducing the native plant seed bank, increasing sedimentation (e.g., ecosystem engineering), and altering the fish community equilibrium to favor littoral fishes over pelagic fishes (Yarrow et al. 2009, Conrad et al. 2016).

Seventeen active ingredients are currently labeled by the U.S. Environmental Protection Agency (US EPA) for use to control aquatic vascular plants and algae (AERF 2019). Two of these, glyphosate and imazapyr, have no herbicide activity on submersed plants, only on emergent foliage (Netherland 2014). Of the remaining fifteen herbicides, the auxinic acids 2,4-D and triclopyr and the algaecide hydrogen peroxide are unlikely to have activity on egeria (Pennington 2014). The most likely remaining candidates to control egeria are six contact herbicides and five systemic herbicides.

Contact herbicides act only on foliage exposed to the herbicide (Shaner 2014). Although this is less desirable, contact herbicides have the more desirable traits in water of rapid uptake, short exposure time requirements, and rapid herbicide activity (Netherland 2014). Carfentrazone is unusual as a contact herbicide, in that it is selective in controlling broadleaved plants (Shaner 2014). It is widely used in row crops, rice, turf, pastures, and in vegetation management (Shaner 2014). Carfentrazone is a protoporphyrinogen (PPO) inhibitor that is sensitive to solution pH (Netherland 2014). Copper herbicides are utilized to control submersed plants and algae, usually complexed with a number of chelating agents. Copper chelates are safe for use in drinking water reservoirs and irrigation canals, but have come under some scrutiny by state and federal regulators for concerns regarding toxicity to mollusks, macroinvertebrates, and some fish species (Chakoumakos et al. 1979, Mastin and Rodgers 2000, Wagner et al. 2017). Endothall is used in two formulations, the dimethylalkylamine salt and the dipotassium salt. The two formulations are different in terms of ecotoxicology and herbicidal activity (Madsen 2000). In recent years, both endothall formulations have been labeled for use in irrigation water and have become widely used to control submersed plants and algae in irrigation canals (Netherland 2014). Flumioxazin is another PPO inhibitor, but has a broader spectrum of activity. It is active on emergent, floating, free-floating, and submersed plants and on filamentous algae (Netherland 2014).

Five systemic herbicides are also available that might assist with management of egeria. Bispyribac-sodium is an acetolactate synthase (ALS) inhibitor that is primarily used for the control of grass and sedge weeds in rice cultivation (Shaner 2014). When used to control hydrilla [*Hydrilla verticillata* (L.f.) Royle] in Florida, it requires an extended exposure time (Netherland 2014). Florpyrauxifen-benzyl is an arylpicolinate herbicide used for rice cultivation, and newly introduced to aquatic use (Netherland and Richardson 2016). Although classed as an auxin mimic, it has efficacy on some monocots, including hydrilla, with potential uses for both emergent and submersed plants (Richardson et al. 2016). Fluridone is an aquatic herbicide that inhibits the production of carotenoids (Shaner 2014). It has been widely used as a systemic herbicide where longer-term exposure is possible (Netherland 2014). Imazamox is an ALS inihibitor used in row crops, particularly as part of the Clearfield® cropping system (Shaner 2014). Penoxsulam is an ALS inhibitor used in rice cultivation that is a broad-spectrum control for grasses and forbs (Shaner 2014). For aquatic sites, it can be applied foliarly on emergent weeds or injected for submersed weeds (Netherland 2014).

A variety of techniques have been used to control egeria. The most common biological control has been the use of grass carp [*Ctenopharyngodon idella* (Valenciennes in Cuvier and Valenciennes, 1844), with long-term control reported (Bonar et al. 1993]. Although researchers have found candidates for insect biological control, the most recent candidate was found to feed on congener common waterweed (*Elodea canadensis* Michx.) in feeding tests (Cabrera Walsh et al. 2013, Pratt et al. 2019). Several herbicides have been tested against egeria, but the herbicides most commonly used to control egeria in the United States are chelated copper (Pennington 2014), diquat (Poovey and Getsinger 2002, Parsons et al. 2007), and fluridone (Parsons et al. 2009). Harvesting has been used in some waters to manage egeria (Pennington 2014). In reservoirs and regulated waters, winter drawdown has been used to control egeria with variable success (Hestand and Carter 1974, Dugdale et al. 2012).

Managing invasive aquatic plants within the Delta carries multiple layers of regulatory compliance. Any program requires compliance with the California Environmental Quality Act. In addition, operations must mitigate any potential impacts to endangered species in both the federal Endangered Species Act (ESA) and the state ESA by Biological Opinions (BO) in consultation with the U.S. Fish and Wildlife Service (USFWS), National Marine Fisheries Service (NMFS), and the California Department of Fish and Wildlife (CDFW). Water quality compliance, in particular related to the use of aquatic herbicides, requires compliance with federal (Federal Insecticide, Fungicide, and Rodenticide Act [FIFRA] and Clean Water Act [CWA]) and state regulations (Porter Cologne Act). Herbicides used in the program must comply with FIFRA, be registered by the US EPA and by the California Department of Pesticide Registration. Federal and state National Pollutant Discharge Elimination System (NPDES) regulations must be complied with as well. To use an aquatic herbicide, it has to be listed with the California State Water Resources Control Board, which is an additional process. The regional water quality board (in this case, the Central Valley Regional Water Quality Control Board) must also approve the Aquatic Plant Management Plan. Because there are hundreds of irrigation water intakes, herbicide applications must be cognizant of irrigation restrictions. Herbicide applications must also be reported to the County Agriculture Commissioner in each county within the Delta and comply with pertinent agricultural filing or setbacks. Any physical or mechanical

TABLE 1. U.S. ENVIRONMENTAL PROTECTION AGENCY-LABELED AQUATIC HERBICIDES USED IN A STATIC EXPOSURE TRIAL ON BRAZILIAN EGERIA AT AN OUTDOOR MESOCOSM FACILITY IN DAVIS, CA. TABLE PROVIDES THE ACTIVE INGREDIENT, TRADE NAME, MANUFACTURER, AND APPLIED CONCENTRATION OF ELEVEN AQUATIC HERBICIDES. ARABIC NUMBERS WITH THE TRADE NAME REFERENCE THE SOURCE OF MATERIALS THAT LISTS THE MANUFACTURERS CONTACT INFORMATION. NOTE: FLORPYRAUXIFEN-BENZYL WAS NOT USED IN THE 2016 MESOCOSM TRIAL.

Active Ingredient	Trade Name	Manufacturer	Concentration (μg L^{-1})
Bispyribac Sodium	Tradewind[1]	Nufarm	45
Carfentrazone-ethyl	Stingray[2]	SePRO	200
Copper Ethylenediamine Chelate	Harpoon[3]	Applied Biochemists	1,000
Diquat	Reward[4]	Syngenta	390
Endothall (Dipotassium salt)	Aquathol-K[5]	United Phosphorus	5,000
Endothall (Dimethylalkylamine salt)	Hydrothol 191[6]	United Phosphorus	5,000
Florpyrauxifen-benzyl	ProcellaCOR[7]	SePRO	50
Flumioxazin	Clipper[8]	Nufarm	400
Fluridone	Sonar AS[9]	SePRO	60
Imazamox	Clearcast[10]	SePRO	500
Penoxsulam	Galleon[11]	SePRO	60

control operations must be approved by the U.S. Army Corps of Engineers under Section 404, as impacting navigable waters.

During the 1990s, some trials were performed in the Delta to control egeria with chelated copper herbicides (Lars Anderson, pers. comm.). From 2000 to 2005, diquat was used in limited acreages (24 to 69 ha [60 to 170 acres]) to control egeria (CDBW 2017). Trials were also done with fluridone during this period (35 to 227 ha [87 to 560 acres]), but from 2006 to 2016 only fluridone has been used operationally, in treatments from 89 to 1,540 ha yr^{-1} (220 to 3,800 acres yr^{-1}) (CDBW 2017). Since 2006, the California State Parks Division of Boating and Waterways (hereafter "CDBW") has managed this species with granular fluridone treatments, treating between 600 and 1,200 ha yr^{-1} (1,500 and 3,000 acres yr^{-1}) (CDBW 2017). Recently, this has taken the form of 16 weekly treatments in the selected treatment zones, targeting a rate of 5 to 20 μg L^{-1}, to maintain a fluridone concentration of 2 to 5 μg L^{-1} (CDBW 2018). Although adequate control has been achieved in many areas, some areas do not receive adequate control under this treatment regime, likely due to water exchange and inadequate exposure time. In addition, some areas cannot be treated due to proximity to irrigation water intakes or other regulatory issues (CDBW 2018). Alternatives to the exclusive use of fluridone are needed in the long term for egeria management.

We designed a mesocosm study to evaluate 11 herbicides for their ability to control egeria. We also performed field demonstration evaluations on three of these herbicides: fluridone, diquat, and the dipotassium salt of endothall.

MATERIALS AND METHODS

Mesocosm trial 2016

Egeria were grown and treated in a small-tank mesocosm facility at the USDA Aquatic Weed Research Laboratory, Davis, CA. The facility has 50 tanks of 150 L capacity, with a potential 125 L volume for treatment. Four 4.2-L pots were filled with Modified UC–Davis Mix for each tank, and two 15 cm (6-inch) stems of egeria sprigged into each pot. Modified UC mix is a soil composed of 90% sand and 10% organic soil (peaty soil) amended with specific amounts of nitrate, potassium, sulfate, and superphosphate (Spencer and Anderson 1986). Plants were allowed to grow for 4 wk before treatment. Ten herbicide treatments and the untreated reference were randomly assigned to the tanks, with 4 replicates $treatment^{-1}$ (Table 1). Additional tanks for a pretreatment biomass level were harvested within 2 d before treatment, to establish a biomass at the time of treatment. Visual assessments of control in each tank were recorded weekly. Treatments were static, and water was retained in the tanks for 8 wk (56 d). However, water levels were maintained by adding water to the filling line three times each week to counteract evaporation. At the end of 8 wk, the pots were harvested, rinsed, and plant shoot biomass dried at 70 C and weighed.

Mesocosm trial 2018

The experiment was repeated as in 2016, except with an additional herbicide. Eleven herbicides were tested in a 50-tank mesocosm facility (tanks are 167 L each) on the grounds of the USDA Agricultural Research Service (ARS) Aquatic Weed Research Laboratory, Davis, CA. Four 4.2-L pots with egeria planted in a Modified UC Mix were placed in each tank, and filled from a domestic water supply. Plants were grown for 4 wk before treatment. The 11 herbicides were treated in each of four randomly selected tanks (Table 1), with four tanks as an untreated control and two tanks harvested on the treatment day as an estimate of pretreatment biomass. After 10 wk of static exposure, water was drained, pots harvested, and shoot biomass dried for at least 48 h at 70 C. Statistical comparisons were made using a one-way ANOVA, post-hoc comparisons of the mean by a Bonferroni Significant Difference test at the $P = 0.05$ level.

Field trial assessment methods

Each treatment plot was assessed by biomass sampling using an Ekman dredge (Madsen 1993). The samples were sorted to species, dried at 70 C for at least 48 h, and weighed. Plots were also assessed by point intercept using at least 30 points $plot^{-1}$ (Madsen and Wersal 2017).

Table 2. Field evaluation study sites and global positioning system (GPS) locations (decimal degrees) for the fluridone evaluation (2016), the diquat evaluation (2018), and the endothall evaluation (2018) in the Sacramento–San Joaquin River Delta.

Study Plot	Field Study	Treatment or Reference	Latitude (°N)	Longitude (°W)
Fourteen Mile Slough	Fluridone 2016	Treatment	37.993653	−121.360149
Rock Slough	Fluridone 2016	Treatment	37.974709	−121.603439
Hog Island	Fluridone 2016	Treatment	38.032224	−121.473693
Disappointment Slough	Fluridone 2016	Reference	38.039175	−121.439836
Connection Slough	Fluridone 2016	Reference	37.995866	−121.574308
Columbia Slough	Fluridone 2016 Diquat 2018	Reference	38.039112	−121.498051
Cabrillo Bay	Diquat 2018	Treatment; Fluridone fb[1] Diquat	37.909519	−121.605138
Indian Slough	Diquat 2018	Treatment, Diquat	37.916703	−121595290
Middle River	Endothall 2018	Treatment, Endothall	37.886582	−121.397356

[1]fb, followed by.

Fluridone field trial

Operational treatments of egeria with fluridone were assessed at three treated sites (Fourteenmile Slough, Rock Slough, and Hog Island) and three untreated reference sites (Disappointment Slough, Connection Slough, and Columbia Slough; Table 2). Ten biomass samples were taken in each plot in April, July, and September of 2016. Herbicide treatments were made of granular fluridone products (Sonar Q, Sonar One, or Sonar PR) at rates of 5 to 20 μg L^{-1}, to maintain an in-water fluridone concentration of 2 to 5 μg L^{-1} (CDBW 2017). Treatments began the week of March 7, 2016 and continued weekly for 12 wk (2016 protocol).

Diquat field trial

A diquat demonstration field trial was implemented at three sites (Table 2). One site (Columbia) was an untreated reference site, one site (Cabrillo in the Discovery Bay community) had been treated for 16 wk with fluridone without effect, and was treated once, and one site (Indian Slough) was treated with just diquat. Treatments were completed on August 30 and September 11 targeting the label rate of 370 μg L^{-1}. The plots were sampled before treatment (June 2018) and 8 wk after treatment (WAT) (December 2018) with 15 biomass samples $site^{-1}$.

Endothall field trial

In response to an urgent request from an irrigation district, a plot on the Middle River (Table 2) in the extreme southern portion of the Delta was treated with the dipotassium salt of endothall (Aquathol K) on October 25 and November 1 targeting a label rate of 5 mg L^{-1}. The plant community was a mix of species including egeria, coontail, Eurasian watermilfoil, and fanwort. Pretreatment samples were taken on October 25, 2018 and one posttreatment sample after the first treatment was taken on December 11, 2018. A sample after the second treatment was not possible due to the government shutdown. Ten biomass samples were taken using an Ekman dredge.

Statistical analyses were performed with Statistix 10.0 Analytical Software[12].

RESULTS AND DISCUSSION

Mesocosm trial 2016

For the 2016 trial, only the chelated copper, diquat, and dimethylalkylamine salt of endothall biomass was significantly lower than the reference (Figure 1). The reference tanks, however, had exceptionally high variability in the resulting biomass, reducing the power of statistical comparison. A one-way ANOVA found a significant difference between the treatments ($P = 0.0036$). These results suggest that copper chelate, diquat, and endothall dimethylalkylamine formulations are effective for controlling egeria, and other herbicides were at least suppressing egeria growth.

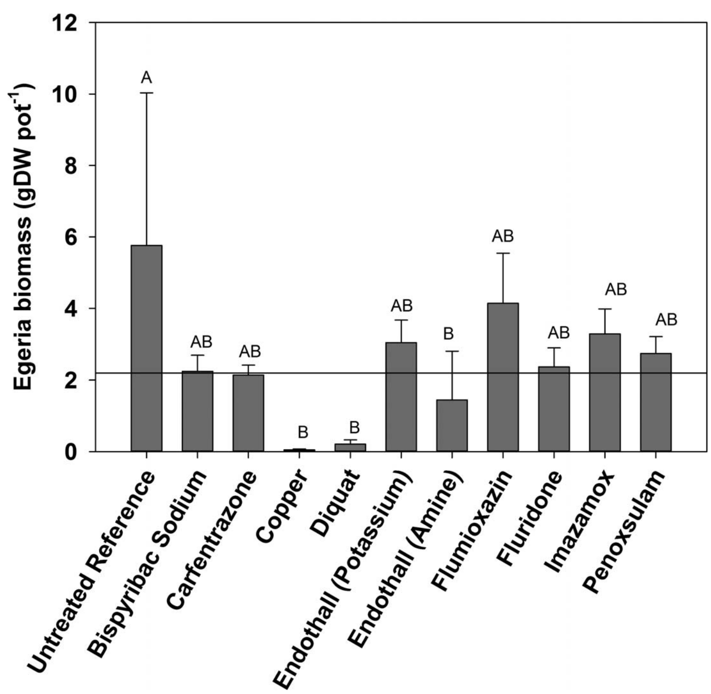

Figure 1. Biomass (g dry weight [DW] pot^{-1}) of egeria after treatment with 1 of 10 herbicides in an 8-wk exposure versus the untreated reference in an outdoor mesocosm trial in Davis, CA during 2016. Means with a difference letter are significantly different at the $P = 0.05$ level. Common name of the active ingredient is provided on the X axis. The treatments are significantly by a one-way ANOVA ($P = 0.0036$). Copper in the figure is copper ETH chelate.

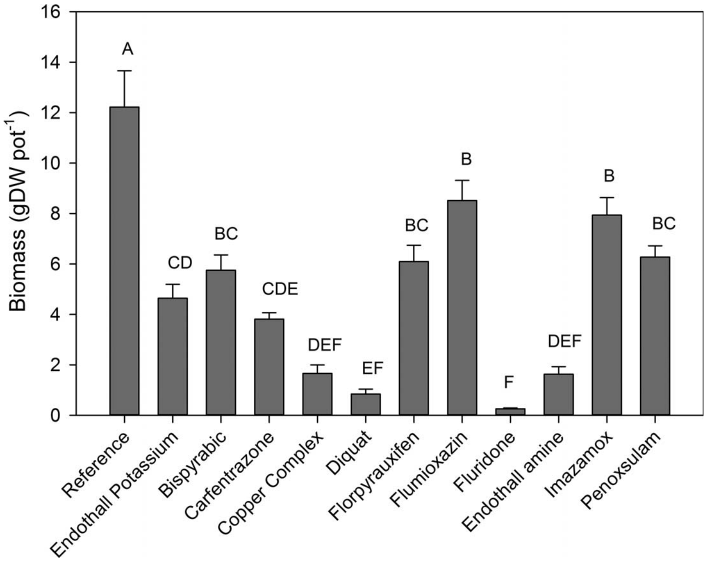

Figure 2. Biomass (g dry weight [DW] pot^{-1}) of egeria after treatment with 1 of 11 herbicides in a 10-wk exposure versus the untreated reference in an outdoor mesocosm trial in Davis, CA during 2018. Means with a difference letter are significantly different at the $P = 0.05$ level. Common name of the active ingredient is provided on the X axis. The treatments are significantly by a one-way ANOVA ($P < 0.0001$). Copper in the figure is copper ETH chelate.

This study supports the conclusions of the following mesocosm study completed in 2018.

Mesocosm trial 2018

All herbicides tested provided significant biomass reduction compared to the untreated reference by 10 WAT (Figure 2). An ANOVA indicated a significant difference between the mean biomass of treatments ($P < 0.0001$). Fluridone, the dimethylalkylamine salt of endothall, copper chelate, and diquat reduced biomass by more than 80%, and were significantly better than all of the others, except carfentrazone-ethyl (Figure 2, Table 3). Although fluridone provided the best control in the mesocosm trial, it does not always provide control in some locations of the Delta, particularly sites which have high water exchange. Fluridone cannot be used in additional locations because of proximity to irrigation water intakes. Fluridone has an irrigation water residue restriction. Although Wells et al. (1986) found that fluridone was not effective on egeria in small-scale trials, other trials found otherwise. Laboratory assessment of the response of egeria to fluridone exposure found that phytoene buildup and beta-carotene suppression were comparable to that observed in hydrilla and Eurasian watermilfoil; Sprecher et al. 1998). Tanaka et al. (2002) found better than 99% control with fluridone both at small scales and in a pond setting.

Diquat could be used to replace fluridone in some high exchange sites, but the current Biological Opinions from USFWS and NMFS only allows diquat to be used in 61 ha yr^{-1} (150 acres yr^{-1}. As in this study, other small-scale studies have documented the effectiveness of diquat for controlling egeria. Martins et al. (2005) found that two treatments of diquat at 0.5 mg L^{-1} were sufficient to fully control egeria. Skogerboe et al. (2006) found that 0.37 ppm of diquat was effective in controlling egeria, even in flowing water conditions. One consideration in using diquat, however, is that inorganic turbidity in the water can adversely affect diquat efficacy, because diquat binds to particulate matter (Hofstra et al. 2001, Poovey and Getsinger 2002)

The dimethylalkylamine salt of endothall has significant issues with fish toxicity, and cannot be used in areas that serve as fish habitat. Copper chelates are effective, and have been used in nearby waters, but are not allowed within the Delta due to concerns for endangered fish sensitivity. Carfentrazone-ethyl is ranked next at fifth, but it cannot be used in California until approval under NPDES by the California State Water Resources Control Board. The dipotassium salt of endothall is allowed in the new Biological Opinion (BO), and has established irrigation tolerances. However, conventional wisdom is that dipotassium salt of endothall is not effective on egeria (Pennington 2014). Although the dipotassium salt of endothall would not be considered use in other jurisdictions, other alternatives are not available for the Delta, so multiple treatments with dipotassium salt of endothall might provide sufficient control of egeria and provide an alternative to fluridone and the limited use of diquat, with further evaluation. Because it has food tolerances established for irrigation, it might be a suitable alternative in areas closer to irrigation water intakes. Hofstra and Clayton (2001) found that the

Table 3. Ranked list of the herbicides tested against egeria in a mesocosm experiment at the U.S. Department of Agriculture Agricultural Research Service (USDA ARS) Aquatic Weed Research Laboratory, Davis, CA in 2018. List includes herbicide common name, trade name of formulation used, percent control calculated from biomass data at 10 wk after treatment (WAT), and the usage issue in the Delta.

Herbicide Common Name	% Control	Usage Issue in the Delta
Fluridone	98	Long exposure time, irrigation restriction
Diquat	93	Limited acreage allowed (61 ha [150 acres])
Endothall Dimethylamine salt	87	Fish toxicity
Copper Ethylenediamine Chelate	87	ESA listed fish species sensitivity
Carfentrazone-ethyl	69	Irrigation restriction, not yet approved in CA
Endothall Dipotassium salt	62	Conventional wisdom, not effective
Bispyrabic Sodium	53	Not approved in Biological Opinion (BO), irrigation restriction
Florpyrauxifen-benzyl	50	Not yet labeled in CA
Penoxsulam	49	Irrigation restriction, long exposure time
Imazamox	35	Low efficacy
Flumioxazin	30	Low efficacy, irrigation restriction

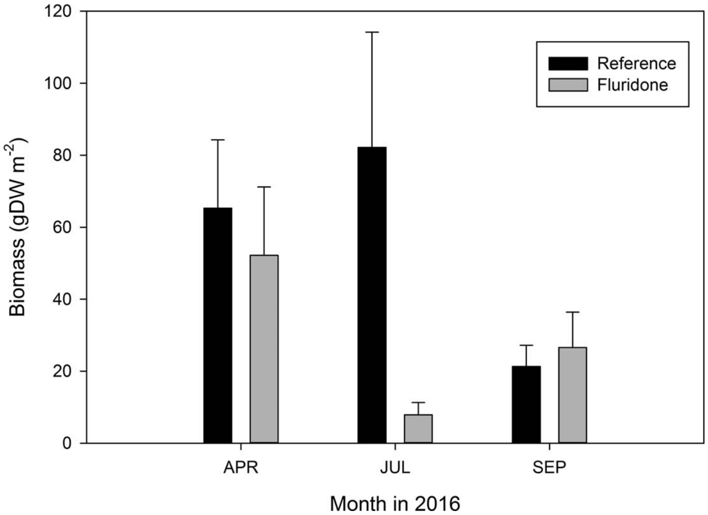

Figure 3. Field evaluation of a fluridone treatment to control egeria biomass (g dry weight [DW] m^{-2}) in April, July, and September of 2016. Treatments began in March 2016. July 2016 biomass indicates 85% control. The July mean between the treated and untreated plots was significantly different by a *t*-test ($P = 0.028$).

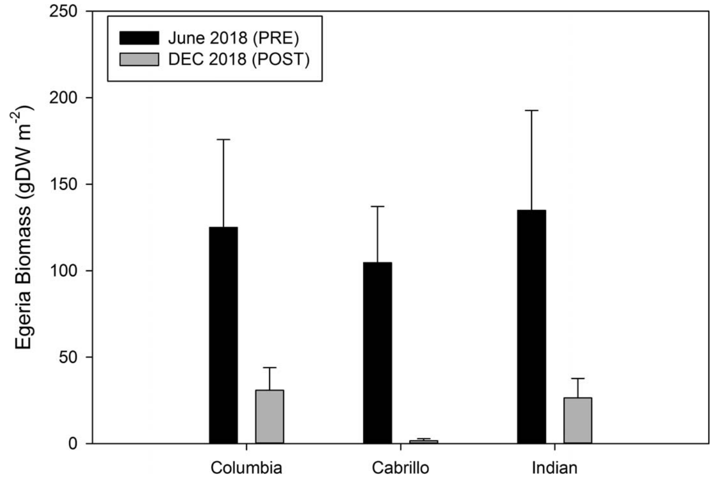

Figure 4. Field evaluation of a diquat treatment to control egeria during 2018. Biomass (g dry weight [DW] m^{-2}) of egeria is shown before (June 2018) and after (December 2018) treatment. Columbia is an untreated reference, Cabrillo was treated 16 wk with fluridone, then treated with diquat after lack of control, and Indian was only treated with diquat.

dipotassium salt of endothall was not effective for controlling egeria.

Standard recommendations in the rest of the United States for control of egeria suggest using chelated copper, diquat, combination treatments of chelated copper and diquat, or fluridone (Westerdahl and Getsinger 1988, Pennington 2014). In fishless waters, the dimethylalkylamine salt of endothall can be used (Westerdahl and Getsinger 1988).

Fluridone field trial

Fluridone provided an average of 85% control over the three plots sampled in this operational treatment, but the egeria regrew by September (Figure 3). The July mean between the treated and untreated plots was significantly different by a *t*-test ($P = 0.028$). To be effective, fluridone must be applied in the same plot for multiple years to deplete stored carbohydrates. Fluridone treated at 20 µg L^{-1} was used to successfully control egeria, along with *Egeria najas* (Planch.) and coontail in Tiete River reservoir in Brazil (Marcondes et al. 2003). In the State of Washington, fluridone treatments at 12 µg L^{-1} maintained for 8 wk reduced egeria frequency of occurrence by 86%, and egeria biomass by 98% (Parsons et al. 2009).

Diquat field trial

When used as a follow-up to a fluridone treatment, diquat provided 98% control (*t*-test $P = 0.007$, Figure 4). Used alone in Indian Slough, diquat provided 80% control (*t*-test $P = 0.085$). However, long-term effectiveness has not yet been evaluated. In Battle Ground Lake, Washington, diquat treatments at 370 µg L^{-1} were effective in significantly reducing the distribution and abundance of egeria (Parsons et al. 2007). In two instances, combination treatments of diquat and the dipotassium salt of endothall controlled egeria in Chickahominy Reservoir in Virginia (Corning and Prosser 1969, Berry et al. 1975). In a 1967 treatment, the combination was reported to provide complete control for the year of treatment, based on a visual inspection (Corning and Prosser 1969). In a follow-up study, quantitative samples of wet weight found that the treatment reduced the mass of plants 84% by 41 days after treatment (DAT), but plants regrew the following year (Berry et al. 1975).

Endothall field trial

In the Middle River dipotassium salt of endothall trial, the posttreatment data were compared to pretreatment data, as opposed to the other two studies in which there is an untreated site as a reference. Endothall reduced egeria biomass by 43%, Eurasian watermilfoil biomass by 96%, coontail biomass by 94%, and total biomass of all aquatic plants by 60% (Figure 5) after one treatment. However, the biomass was not significantly different between pretreatment and posttreatment samples, likely due to an inadequate sample size. An additional treatment was made, but we were unable to sample after the second treatment due to the government shutdown. CDBW observation suggests additional reduction of egeria after the second treatment.

Further research should be done on the use of diquat and the dipotassium salt of endothall as additional tools to control egeria in the Delta. In addition, carfentrazone-ethyl will be more fully evaluated as an option for egeria management if a California aquatic pesticide label is approved. Given the complexity of the management issues and the strict standards for pesticide toxicity for using herbicides in the Delta as compared to other waters, we will need to investigate other herbicides that could control egeria while complying with the various environmental concerns in the Delta. All of these herbicide tools are used

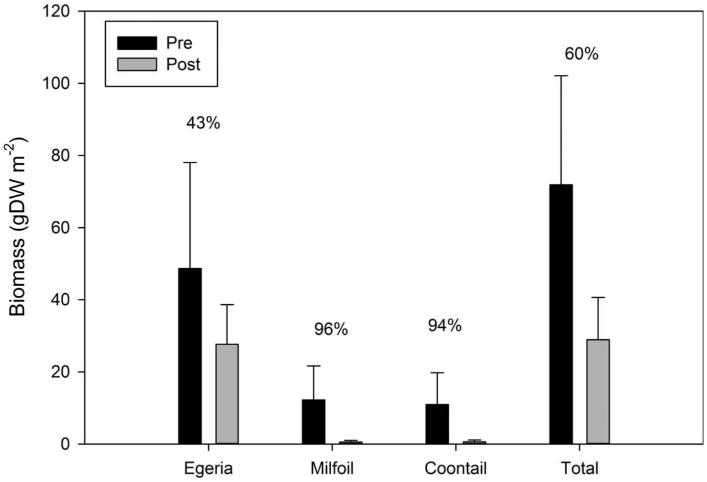

Figure 5. Pre- and posttreatment biomass (g dry weight [DW] m^{-2}) of egeria, Eurasian watermilfoil, coontail, and total biomass of all species in the Middle River during 2018. Percent biomass reduction is indicated above each pair of bars for each species. Middle River was treated with the dipotassium salt of endothall.

in the context of an adaptive integrated pest management approach for the Sacramento–San Joaquin River Delta.

SOURCES OF MATERIALS

[1]Tradewind Herbicide, Nufarm Americas, 11901 South Austin Avenue, Alsip, IL 60803.

[2]Stingray Aquatic Herbicide, SePRO Corporation, 11550 North Meridian Street, Suite 600, Carmel, IN 46032.

[3]Harpoon Aquatic Herbicide, Applied Biochemists, W175n11163 Stonewood Drive, Suite 234, Germantown, WI 53022.

[4]Reward Landscape and Aquatic Herbicide, Syngenta Crop Protection LLC, P.O. Box 18300, Greensboro, NC 24719-8300.

[5]Aquathol-K Aquatic Herbicide, UPL NA Inc., 630 Freedom Business Center, Suite 402, King of Prussia, PA 19406.

[6]Hydrothol 191 Aquatic Algaecide and Herbicide, UPL NA Inc., 630 Freedom Business Center, Suite 402, King of Prussia, PA 19406.

[7]ProcellaCOR SC, SePRO Corporation, 11550 North Meridian Street, Suite 600, Carmel, IN 46032.

[8]Clipper Herbicide, Nufarm Americas, 11901 South Austin Avenue, Alsip, IL 60803.

[9]Sonar AS Aquatic Herbicide, SePRO Corporation, 11550 North Meridian Street, Suite 600, Carmel, IN 46032.

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

[11]Galleon SC, SePRO Corporation, 11550 North Meridian Street, Suite 600, Carmel, IN 46032.

[12]Statistix 10.0, Analytical Software, 2105 Miller Landing Road, Tallahassee, FL 32312.

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