J. Aquat. Plant Manage. 51: 132–135

Notes

Control of smooth cordgrass (*Spartina alterniflora*) seedlings with four herbicides

CARRIE A. KNOTT, E. P. WEBSTER, AND P. NABUKALU*

INTRODUCTION

Smooth cordgrass (*Spartina alterniflora* Loisel.) is a perennial grass native to intertidal saline marshes along the Atlantic and Gulf of Mexico coasts in the United States (Godfrey and Wooten 1979). It has a dense canopy formed by quickly spreading rhizomes. In its native ecosystems, it provides valuable wildlife habitat and is essential to reducing wave energy and accumulating suspended sediments (Redfield 1972, Nepf 1999). Smooth cordgrass has spread worldwide; it was accidentally introduced on the West Coast of the United States in the 1800s (Frenkle and Kunze 1984, Sayce 1988) and has since spread as far north as British Columbia and as far south as California (Frenkle and Kunze 1984). It was also intentionally introduced in China in the 1970s to reclaim coastal areas (Chung 1993, Chung et al. 2004, Zhang et al. 2004). Outside its native ecosystems, smooth cordgrass is an extremely aggressive invader that alters ecosystems so significantly that native biodiversity and habitats can be lost (Callaway and Josselyn 1992, Daehler and Strong 1996, Dumbauld et al. 1997, Chen et al. 2004).

Methods to control smooth cordgrass in nonnative areas have included mechanical, biological, and chemical approaches (Norman and Patten 1996, Portnoy 1999, Hedge et al. 2003, Major et al. 2003, Li and Zhang 2008). Success of smooth cordgrass control has varied and appears dependent on environmental conditions and the frequency with which the control measure is implemented. Typically, mechanical methods, which include various combinations of plant removal, mowing, burial, and flooding, have provided acceptable levels of control of smooth cordgrass; however, they are so expensive that widespread implementation is not feasible (Hedge et al. 2003). Biological controls, which have had limited success, include introduction of insects that suppress growth of smooth cordgrass and substitution of smooth cordgrass with native grasses (Grevstad et al. 2003, Li and Zhang 2008). Chemical control, which uses herbicides to eliminate invasive smooth cordgrass, has had greater success in reliably controlling smooth cordgrass plants in natural environments (Kilbride et al. 1995, Patten 2002 Major et al. 2003). To date, 2 herbicides have been registered by the U.S. Environmental Protection Agency (USEPA) for smooth cordgrass control in estuarine environments in the United States: glyphosate and imazapyr. The focus of most control programs is on established smooth cordgrass plant communities. However, seed dispersal is an important mechanism of invasive smooth cordgrass spread (Daehler and Strong 1997, Anttila et al. 1998). Manual removal of smooth cordgrass seedlings has been used as a control option; however, implementation has been prohibited by its labor requirements and cost (Hedge et al. 2003). Because of its success for established plant communities, chemical control of smooth cordgrass seedlings could be an economical and environmentally acceptable option for controlling invasive smooth cordgrass, which will likely require much lower herbicide rates than established smooth cordgrass plants.

The objectives of this study were to determine (1) control rates of smooth cordgrass seedlings with 4 herbicides; and (2) injury to established smooth cordgrass plants after the application of 4 herbicides.

MATERIALS AND METHODS

To produce smooth cordgrass seedlings, seed was harvested from an aquatic production field, which contained 7 smooth cordgrass cultivars ('Vermilion', 'Cameron', 'Terrebonne', 'Jefferson', 'St. Bernard', 'Las Palomas', and 'Lafourche' [Fine and Thomassie 2000, Knott et al. 2012a,b]) and 6 experimental smooth cordgrass genotypes (unpub. data), in November 2010, in Baton Rouge, LA. Seed was immediately submerged in water outdoors until March 2011, when seeds were planted into Ray Leach Cone-tainer cells[1] containing Pro-Mix potting soil[2] in controlled greenhouse conditions, which was maintained at approximately 25 C (77 F) under natural photoperiod, for 6 wk until they reached the 2-leaf stage and were approximately 13 cm (5.12 in) tall. To produce established smooth cordgrass plants, rhizomes and approximately 35 cm of stem material of 6 smooth cordgrass cultivars ('Cameron', 'Terrebonne', 'Jefferson', 'St. Bernard', 'Las Palomas', and 'Lafourche' [Knott et al. 2012a,b]) were planted in March 2010 into 4-L (1.06 gal) trade containers. Smooth cordgrass plants were allowed to

*School of Plant, Environmental and Soil Sciences, Louisiana State University Agricultural Center, 104 M.B. Sturgis Hall, Baton Rouge, LA 70803. Corresponding author's E-mail:carrie.knott@uky.edu. Current Address: Department of Plant and Soil Sciences, University of Kentucky Research and Education Center, P.O. Box 469, Princeton, KY 42445
Received for publication November 8, 2012 and in revised form March 12, 2013.

TABLE 1. AVERAGE PERCENTAGE OF CONTROL OF SMOOTH CORDGRASS SEEDLINGS 7, 14, 21, 28, AND 63 D AFTER TREATMENT (DAT) FOR 4 HERBICIDES APPLIED IN A GREENHOUSE STUDY, BATON ROUGE, LA, 2011.

Herbicide	7 DAT[1] Average[2]	14 DAT 1×	14 DAT 2×	21 DAT 1×	21 DAT 2×	28 DAT 1×	28 DAT Average	63 DAT
	Control[3] (%)							
Glufosinate	37.0 a	64.8 a	69.4 a	82.9 a	70.4 a	93.1 a	87.0 a	99.5 a
Glyphosate	21.5 b	34.7 b	62.5 a	45.8 b	77.8 a	65.3 b	86.6 a	95.4 b
Imazapyr	6.3 c	13.4 c	14.8 b	19.4 c	31.5 b	29.6 c	44.9 b	92.8 b
Imazethapyr	10.9 c	19.0 c	14.4 b	41.2 b	21.8 b	50.9 b	34.7 b	88.0 c

[1]DAT indicates days after herbicide treatment was applied.
[2]Average indicates that the percentage of smooth cordgrass seedling control was averaged for data collected on 1× and 2× herbicide rates; 1× and 2× indicates the percentage of smooth cordgrass seedling control when 1× and 2× herbicide rates were applied. The 1× and 2× rates, respectively, were 0.82 and 1.64 kg ha^{-1} glufosinate; 1.06 and 2.13 kg ha^{-1} glyphosate; 1.05 and 2.11 kg ha^{-1} imazapyr; and 0.11 and 0.21 kg ha^{-1} imazethapyr.
[3]Averages followed by different letters within each column are statistically different according to the *t* test on difference of least-square means at P = 0.05.

increase in size and become well-established plants for 1 yr until they had approximately 8 stems and were 60 cm tall.

A nontreated control and 4 herbicides applied at 2 rates were examined: 0.82 and 1.64 kg ha^{-1} (0.07 and 1.46 lb ac^{-1}) of glufosinate[3] (ammonium-DL-homoalanin-4-yl(methyl)-phosphinate); 1.06 and 2.13 kg ha^{-1} of glyphosate[4] (5.5 L; N-(phosphonomethyl) glycine); 1.05 and 2.11kg ha^{-1} imazapyr[5] (4 L; 2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-3-pyridinecarboxylic acid); and 0.11 and 0.21 kg ha^{-1} imazethapyr[6] (2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-methyl-3-pyridine-carboxylic acid). Both herbicide rates were experimental; the low rate was referred to as 1× and the high rate as 2×. Currently, only glyphosate and imazapyr are registered for estuarine environments by the USEPA.

Smooth cordgrass seedlings and established plants were moved to a treatment area outside the greenhouses for 45 min before herbicide application to adjust to the treatment environment. Herbicides were applied with a CO_2-pressurized backpack sprayer delivering 140 L ha^{-1} solution at 190 kPa and were allowed to dry for 45 min before plants were moved back into greenhouses. The nontreated control was handled in the same manner.

Percentage of control of smooth cordgrass seedlings and established plants were evaluated 7, 14, 21, 28, and 63 d after treatment (DAT). We also measured injury of established smooth cordgrass plants 7, 14, 21, 28, and 63 DAT because no established plants were controlled with the experimental herbicide rates. Percentage of control of smooth cordgrass seedlings was calculated for each replication as follows:

$$\left(\frac{\textit{No. of dead smooth cordgrass seedlings}}{\textit{Total no. of smooth cordgrass seedlings}}\right) \times 100. \quad [1]$$

Injury of established smooth cordgrass plants was evaluated based on chlorosis and necrosis of foliage using a 0 to 100% scale, where 0% was no injury and 100% was plant death.

The experimental design was a 4 by 2 factorial, randomized, complete block with 4 replications. Each seedling replication had 27 smooth cordgrass seedlings, and each established replication had 6 smooth cordgrass plants (one for each of the 6 cultivars) for a total of 108 seedlings (27 seedlings × 4 replications = 108) and 24 established clonal plants (6 plants × 4 replications = 24) tested per herbicide treatment per experiment. The experiment was completed twice: Trial 1 began on May 6, 2011, whereas Trial 2 began on May 13, 2011. Data for percentage of smooth cordgrass seedling control and injury of smooth cordgrass plants were arcsine square-root transformed and analyzed using PROC MIXED in SAS 9.1.[7] Trial and replication were specified as random effects; herbicide was specified as a fixed effect. Type III statistics were used to test all possible effects of fixed factors and least-square means were used for means separation at the 5% probability level ($P \leq 0.05$). Non-transformed data are reported; data interpretations were based on transformed data.

RESULTS AND DISCUSSION

To determine the feasibility of using herbicides to control smooth cordgrass seedlings, which is an important dispersal mechanism of invasive smooth cordgrass (Daehler and Strong 1997Anttila et al. 1998), we measured percentage of smooth cordgrass seedling control when 4 herbicides were applied at 2 rates. Smooth cordgrass seedling control at 7 DAT ranged from 6.3 to 37.0%; glufosinate provided the greatest control, whereas imazapyr and imazethapyr provided the least smooth cordgrass seedling control (Table 1). Significant herbicide by rate interactions were detected at 14, 21, and 28 DAT; therefore, data are presented for each herbicide rate. When herbicides were applied at 1× rate, smooth cordgrass seedling control at 14 DAT ranged from 13.4 to 64.8%; glufosinate provided the best control, whereas imazapyr and imazethapyr provided the least control (Table 1). At 2× rates at 14 DAT, smooth cordgrass seedlings were controlled 14.4 to 69.4%; glufosinate and glyphosate provided the greatest control, whereas imazapyr and imazethapyr provided the least control (Table 1). Smooth cordgrass seedling control ranged from 19.4 to 82.9% and 29.6 to 93.1% for the 1× herbicide rate at 21 and 28 DAT, respectively; glufosinate provided the greatest control, whereas imazapyr provided the least control at 1× herbicide rates at 21 and 28 DAT (Table 1). When 2× herbicide rates were applied at 21 and 28 DAT, control ranged from 21.8 to 77.8% and 34.7 to 87.0%, respectively; at both times, glufosinate and glyphosate had the best control, whereas imazapyr and imazethapyr had the least control (Table 1). By 63 DAT, 99.5% of seedlings were controlled with glufosinate, whereas only 88% were

Table 2. Average percent injury of established smooth cordgrass plants after 4 herbicide treatments were applied in a greenhouse study, Baton Rouge, LA, 2011.

Herbicide	7 DAT[1] Average[2]	14 DAT Average	21 DAT Average	28 DAT Average	63 DAT 1×	63 DAT 2×
	Injury[3] (%)					
Glufosinate	31.5 a	26.8 a	25.2 a	22.7 a	19.7 b	25.4 a
Glyphosate	17.1 b	20.2 ab	13.4 b	14.1 b	16.4 b	25.0 a
Imazapyr	21.0 b	23.0 a	22.8 a	23.5 a	32.8 a	31.8 a
Imazethapyr	16.2 b	17.4 b	17.4 b	15.7 b	18.1 b	16.2 b

[1]DAT indicates days after herbicide treatment was applied.
[2]Average indicates that the percentage of smooth cordgrass seedling control was averaged for data collected on 1× and 2× herbicide rates; 1× and 2× indicates the percentage of smooth cordgrass seedling control when 1× and 2× herbicide rates were applied. The 1× and 2× rates, respectively, were 0.82 and 1.64 kg ha^{-1} glufosinate; 1.06 and 2.13 kg ha^{-1} glyphosate; 1.05 and 2.11 kg ha^{-1} imazapyr; and 0.11 and 0.21 kg ha^{-1} imazethapyr.
[3]Averages followed by different letters within each column are statistically different according to the *t* test on difference of least-square means at P = 0.05.

controlled with imazethapyr (Table 1). For each evaluation timing, glufosinate consistently provided the best control of smooth cordgrass seedlings.

We also measured percentage of control of established smooth cordgrass; however, none of the herbicides included in this study resulted in death of an established smooth cordgrass plant (data not shown). To determine the effect of the tested herbicides on established smooth cordgrass plants, we measured percentage of injury. Injury of established smooth cordgrass plants at 7 DAT ranged from 16.2 to 31.5% and was greatest for glufosinate (Table 2). Smooth cordgrass plant injury was greatest for glufosinate and imazapyr and the least for imazethapyr at 14 DAT with a range of 17.4 to 26.8% injury (Table 2). Glufosinate and imazapyr provided the greatest injury, whereas glyphosate and imazethapyr produced the least injury at 21 and 28 DAT (Table 2). A significant herbicide by rate interaction was detected at 63 DAT; therefore, each herbicide rate was analyzed separately. Injury was greatest for smooth cordgrass plants when imazapyr was applied at the 1× rate; however, at the 2× rate, glufosinate, glyphosate, and imazapyr all produced significant injury to the plants (Table 2).

Our data indicate that almost-complete control (99.5%) of smooth cordgrass seedlings can be achieved with glufosinate at 63 DAT and that, at 63 DAT, all herbicides and rates provided at least 88% control of smooth cordgrass seedlings. We also found that the herbicide rates investigated in this study provided no control of established smooth cordgrass plants and produced a maximum injury of less than 33%. In previous studies, control of established smooth cordgrass plants was achieved with much greater herbicide rates in estuaries and natural environments (Patten 2002, Major et al. 2003). Patten (2002) examined imazapyr at 1.68 kg ae ha^{-1} and glyphosate at 7.26 and 18.00 kg ae ha^{-1}. Twelve months after herbicide treatment, control of established smooth cordgrass plants with imazapyr ranged from 36 to 99%, whereas control with the low and high glyphosate rates averaged 66 and 87%, respectively (Patten 2002). Major et al. (2003) examined 2 glyphosate rates, 4.2 and 20.2 kg ae ha^{-1}, to control invasive smooth cordgrass plants. Control at 12 mo after treatment with their low glyphosate rate ranged from 0 to 32%, whereas control with the high glyphosate rate ranged from 7 to 89% (Major et al. 2003). In this study, we examined glyphosate at 1.06 and 2.13 kg ai ha^{-1}, which is 0.87 and 1.74 kg ae ha^{-1}, and imazapyr at 1.05 and 2.11 kg ai ha^{-1}, which is 0.83 and 1.66 kg ae ha^{-1}. These rates are significantly less than those that have been reported previously. To our knowledge, this is the first reported account to investigate chemical controls of smooth cordgrass seedlings. Our goal was to identify management options that would reduce herbicide rates necessary for control of invasive smooth cordgrass in natural aquatic ecosystems. As expected, established smooth cordgrass plants were not controlled and were minimally injured with herbicide rates examined in this study. However, we found that glufosinate consistently provided significant control of smooth cordgrass seedlings. Unfortunately, only glyphosate and imazapyr are registered for use in estuarine environments by the USEPA.

Results of this study indicate that seedling control may be an economical option for controlling invasive smooth cordgrass. Additional research, which includes quantitative data, such as plant height, aboveground and belowground biomass rates, and the fate of additional herbicides in estuarine environments, particularly glufosinate, is needed to confirm this report and to obtain special-needs permits or registration (or both) of glufosinate to control smooth cordgrass seedlings in estuarine environments.

SOURCES OF MATERIALS

[1]Ray Leach Cone-tainer cells, Stuewe & Sons, 31933 Rolland Drive, Tangent, OR 97389.

[2]Pro-Mix potting soil, Premier Horticulture Inc., 127 S. 5th Street, Suite 300, Quakertown, PA 18951.

[3]Glufosinate (2.34 EC), Bayer CropScience AG, Alfred-Nobel-Str. 50, D-40789 Monheim am Rhein, Germany.

[4]Glyphosate, Monsanto Company, 800 N. Lindburgh Boulevard, St. Louis, MO 63167.

[5]Imazapyr, BASF Corporation, 100 Campus Drive, Florham Park, NJ 07932-1089.

[6]Imazethapyr (2 AS), BASF Corporation, 100 Campus Drive, Florham Park, NJ 07932-1089.

[7]SAS statistical software Version 9.1.3 for Windows, SAS Institute, 100 SAS Campus Drive, Cary, NC 27513-2414.

ACKNOWLEDGEMENTS

Financial support for this research was provided by National Institute of Food and Agriculture, U.S. Department of Agriculture (USDA-NIFA). The authors also acknowledge the hard work and dedication of all personnel involved in the project, especially Lina Kruth and Matt Voitier. This manuscript is approved for publication by the Director of Louisiana Agricultural Experiment Station as manuscript number 2012-306-7141.

LITERATURE CITED

Anttila CK, Daehler CC, Rank NE, Strong DR. 1998. Greater male fitness of a rare invader (*Spartina alterniflora*, Poaceae) threatens a common native (*Spartina foliosa*) with hybridization. Am. J. Bot. 85:1597–1601.

Callaway JC, Josselyn MN. 1992. The introduction and spread of smooth cordgrass (*Spartina alterniflora*) in south San Francisco Bay. Estuaries 15:218–226.

Chen ZY, Li B, Chen ZY, Chen JK. 2004. Local competitive effects of introduced *Spartina alterniflora* on *Scirpus mariqueter* at Dongtan of Chongming Island, the Yangtze River estuary and their potential ecological consequences. Hydrobiologia 528:99–106.

Chung CH. 1993. Thirty years of ecological engineering with *Spartina* plantations in China. Ecol. Eng. 2:261–289.

Chung CH, Zhou RZ, Xu GW. 2004. Creation of *Spartina* plantations for reclaiming Dongtai, China, tidal flats and offshore sands. Ecol. Eng. 23:135–150.

Daehler CC, Strong DR. 1996. Status, prediction, and prevention of introduced cordgrass (*Spartina* spp.) invasions in Pacific estuaries, USA. Biol. Conserv. 8:51–58.

Daehler CC, Strong DR. 1997. Hybridization between introduced smooth cordgrass (*Spartina alterniflora*: Poaceae) and native California cordgrass (*S. foliosa*) in San Francisco Bay, California, USA. Am. J. Bot. 84:607–611.

Dumbauld BR, Peoples M, Holcomb L, Ratchford S. (1997) The potential influence of the aquatic weed *Spartina alterniflora* and control practices on clam resources in Willapap Bay, Washington, pp. 51–57. In: K. Patten (*ed.*). Proceedings of the Second International *Spartina* Conference. Washington State University, Olympia, WA.

Fine G, Thomassie G. (2000) 'Vermilion' smooth cordgrass. USDA-NRCS Golden Meadow Plant Materials Center, Galliano, LA. 2 pp.

Frenkle RE, Kunze LM. 1984. Introduction and spread of three *Spartina* species in the Pacific Northwest. Assoc. Am. Geogr. 4:22–25.

Godfrey RK, Wooten JW. 1979. Aquatic and wetland plants of the southeastern United States: Monocotyledons. University of Georgia Press, Athens.

Grevstad FS, Strong DR, Garcia-Rossi D, Switzer RW, Wecker MS. 2003. Biological control of *Spartina alterniflora* in Willapa Bay, Washington using the planthopper *Prokelisia marginata*: Agent specificity and early results. Biol. Control 27:32–42.

Hedge P, Kriwoken LK, Patten K. 2003. A review of *Spartina* management in Washington State US. J. Aquat. Plant Manage. 41:82–90.

Kilbride KM, Paveglio FL, Grue CE. 1995. Control of smooth cordgrass with Rodeo in southwestern Washington estuary. Wildl. Soc. Bull. 23:520–524.

Knott CA, Materne MD, Utomo H, Subudhi PK, Baisakh N, Harrison SA. 2012a. Registration of 'St. Bernard', 'Las Palomas' and 'Lafourche' smooth cordgrass cultivars. J. Plant Reg. 7:12–17.

Knott CA, Materne MD, Utomo H, Subudhi PK, Baisakh N, Harrison SA. 2012b. Registration of smooth cordgrass cultivars 'LA11-101', 'LA11-102', and 'LA11-103'. J. Plant Reg. 6:252–258.

Li H, Zhang L. 2008. An experimental study on physical controls of an exotic plant *Spartina alterniflora* in Shanghai, China. Ecol. Eng. 32:11–21.

Major WW, III, Grue CE, Grassley JM, Conquest LL. 2003. Mechanical and chemical control of smooth cordgrass in Willapa Bay, Washington. J. Aquat. Plant Manage. 41:6–12.

Nepf HM. 1999. Drag, turbulence, and diffusion in flow through emergent vegetation. Water Resour Res 35:479–489.

Norman M, Patten K. 1996. Evaluation of mechanical methods and herbicide/adjuvant treatments for effective control of *Spartina* spp. Final report to the US Department of Commerce (Grant No. NA46FD0396), Washington State University, Long Beach. 10 pp.

Patten K. 2002. Smooth cordgrass (*Spartina alterniflora*) control with imazapyr. Weed Technol. 16:826–832.

Portnoy JW. 1999. Salt marsh diking and restoration: Biogeochemical implications of altered wetland hydrology. Environ. Manage. 24:111–120.

Redfield AC. 1972. Development of a New England salt marsh. Ecol. Monogr. 42:201–237.

Sayce K. 1988. Introduced cordgrass *Spartina alterniflora* Loisel in salt-marshes and tidelands of Willapa Bay, Washington, US Fish and Wildlife Service FWSI-87058 TS, Washington, DC. 70 pp.

Zhang RS, Shen YM, Lu LY, Yan SG, Wang YH, Li JL, Zhang ZL. 2004. Formation of *Spartina alterniflora* salt marshes on the coast of Jiangsu Province, China. Ecol. Eng. 23:95–105.