Pushing toward Cogongrass (*Imperata cylindrica*) Patch Eradication: The Influence of Herbicide Treatment and Application Timing on Cogongrass Rhizome Elimination

Jatinder S. Aulakh, Stephen F. Enloe, Nancy J. Loewenstein, Andrew J. Price, Glenn Wehtje, and James H. Miller*

Cogongrass, an invasive grass native to Asia, has infested thousands of hectares in the southeastern United States. Although numerous studies have examined cogongrass control, no published studies, to our knowledge, have tested strategies for cogongrass eradication. Cogongrass has a persistent, thick rhizome mat but an ephemeral seedbank; therefore, successful eradication methods must largely focus on the rhizomes. A field study to evaluate specific herbicide treatments and application timings for cogongrass patch eradication was conducted at two locations in southwestern Alabama. Herbicide treatments included glyphosate at 4.48 kg ai ha^{-1}, imazapyr at 0.84 kg ai ha^{-1}, and a tank mix of glyphosate and imazapyr at the same rates. Treatments were applied in May, August, or October for 3 consecutive yr, and the May glyphosate treatment included a second annual application each October. Cogongrass visual control, shoot biomass, rhizome biomass, rhizome depth, and total nonstructural carbohydrate (TNC) content were sampled during the course of the study. Cogongrass response to treatments varied by location but by 36 mo after initial treatment (MAIT), complete elimination of cogongrass shoot and rhizome biomass and 100% visual control was achieved in several herbicide treatment–timing combinations at both locations. These included glyphosate plus imazapyr at any application timing, imazapyr in August or October, and glyphosate applied in May and October each year. TNC levels of surviving healthy rhizomes were not affected by herbicide treatments, but a seasonal pattern was observed. The maximum live-rhizome depth was not influenced by any treatment, indicating that herbicides were not preferentially leaving deeper, surviving rhizomes. These results demonstrate, for the first time, that the entire rhizome layer of cogongrass can be eliminated within 3 yr with multiple treatment options and that cogongrass patch eradication is possible for many land managers.

Nomenclature: Glyphosate; glyphosate plus imazapyr; imazapyr; cogongrass, *Imperata cylindrica* (L.) Beauv. IMPCY.

Key words: Cogongrass, application timing, eradication, herbicide, rhizome elimination.

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* First, second, and fifth authors: Graduate Research Assistant, Associate Professor, and Professor, Department of Agronomy and Soils, Auburn University, Auburn, AL 36849; third author: Extension Specialist, School of Forestry and Wildlife Sciences, Auburn University, Auburn AL 36849; fourth author: Plant Physiologist, National Soil Dynamics Laboratory, Agricultural Research Service, U.S. Department of Agriculture, 411 South Donahue Drive, Auburn, AL 36852; sixth author: Research Ecologist (Emeritus), G. W. Andrews Forestry Sciences Laboratory, U.S. Department of Agriculture, Forest Service, 521 Devall Drive, Auburn, AL 36849. Corresponding author's email: jsa0005@tigermail.auburn.edu

The term *weed eradication* is often misinterpreted to mean *weed control*, especially by public policy makers; however, the terms are not synonymous (Zamora et al. 1989). *Eradication* is broadly defined as the destruction of every propagule of a species from an area, with sufficient natural or constructed barriers to prevent reinvasion (Newsom 1978; Zamora et al. 1989). Eradication is clearly a difficult prospect, and there is a widespread view that it is not generally feasible for most invasive plants. However, several weed eradication projects have been successful, including the eradication of southern sandbur (*Cenchrus echinatus* L.) from Laysan islands in northwestern Hawaii

Management Implications

Cogongrass is one of the most difficult weeds to manage because of its aggressive growth and persistent rhizomes, which often survive initial herbicide treatments. Historically, research efforts have been focused on cogongrass control, but no published studies have tested strategies for eradication. The present study is the first documented research to demonstrate complete elimination of cogongrass in 18 to 36 mo using repeated, annual herbicide applications. Treatments included glyphosate, imazapyr, and a tank-mix of both applied in the spring, summer, or fall for 3 consecutive yr. Verification of eradication was based on a highly rigid criterion involving measurements of cogongrass visual control, shoot biomass, rhizome biomass, rhizome depth, and total nonstructural carbohydrate (TNC) content over 3 yr. Cogongrass response to treatments varied by location. By 36 mo after initial treatment, the glyphosate plus imazapyr treatment applied at any timing, the imazapyr treatment applied in August or October, and the glyphosate treatment applied in May and October each year resulted in complete elimination of cogongrass shoot and rhizome biomass. The maximum live-rhizome depth (16 cm $\pm$ 2 SE) was not influenced by any treatment. During the 3-yr period, herbicides did not affect TNC levels of surviving rhizomes, indicating that repeated treatments directly killed rhizomes, rather than slowly exhausting energy reserves. We are not suggesting that cogongrass can be eradicated from the southeastern United States; however, with repeated glyphosate or imazapyr herbicide treatments, land managers do have a feasible means of eradicating cogongrass patches.

(Flint and Rehkemper 2002) and killer alga [*Caulerpa taxifolia* (Vahl) C. Agardh] from southern California (Merkel and Associates 2006). Additionally, the costs and rigors of invasive species eradication can be very high. For example, the effort to eradicate witchweed [*Striga asiatica* (L.) Kuntze] in the southeastern United States has cost more than US$100 million (Eplee 2001). Nevertheless, when eradication is feasible, it may be more cost-effective in the long run than any other control method (Wittenberg and Cock 2001).

An excellent example highlighting this control vs. eradication issue is cogongrass [*Imperata cylindrica* (L.) Beauv. var. *major* tribe Andropogoneae]. Cogongrass is a highly invasive, rhizomatous, perennial grass, which has been ranked as the seventh most-troublesome weed worldwide (Falvey 1981; Holm et al. 1977; MacDonald 2004). At present it occupies more than 500,000 ha in the United States and is classified as a noxious weed in Alabama, Florida, Georgia, Louisiana, Mississippi, Oregon, South Carolina, Texas, and Virginia (Bryson and Carter 1993; Byrd and Bryson 1999; Faircloth et al. 2005; Patterson and McWhorter 1980; Patterson et al. 1983; Van Loan et al. 2002; Willard 1988; Willard et al. 1990). Cogongrass is well recognized for its adverse economic and ecological effects on forestry and natural areas across the southeastern United States through its pyrogenic nature (Lippincott 2000) and its interference with native and desirable vegetation (Jose et al. 2002; Miller 2000).

Historically, cogongrass research emphasized control using numerous chemical and nonchemical methods but did not address eradication (Akobundu 1993; Byrd and Bryson 1999; Johnson et al. 1999; MacDonald et al. 2002; Miller 2000; Ramsey et al. 2003; Willard et al. 1997). Glyphosate and imazapyr have been identified as the most-effective herbicides for cogongrass management (Dozier et al. 1998; Udensi et al. 1999). Repeated applications of these herbicides for multiple years have been reported to provide $>$ 95% control (Miller 2007). These studies generally tested herbicide treatments with one or two applications and evaluated the cogongrass response 12 to 24 MAT. In no case did those treatments result in eradication.

Studies have shown that fall-season applications (September to November) of glyphosate or imazapyr are more effective due to better translocation of herbicides to the underground rhizomes as photosynthates are directed toward rhizomes in the fall (Faircloth et al. 2005; Johnson 1999, 2000; Miller 2007; Shilling et al. 1997). Those previous findings have provided solid recommendations for cogongrass control. However, to date, no long-term research, to our knowledge, investigating those methods for complete eradication of cogongrass patches has been published.

Cogongrass seeds are very short lived in the environment (MacDonald 2004) and do not likely contribute substantially to the challenge of cogongrass patch eradication. Researchers have observed low spikelet fill (0 to 40%), short seed viability ($<$ 16 mo), and poor seedling survival (Dickens 1976; Hopkins and Graham, 1984; Kushwaha et al. 1983; Sajise 1972; Santiago 1974, 1980). Additionally, glyphosate and imazapyr herbicide treatments have reduced cogongrass cover and seedhead production more than 80% and 97%, respectively, up to a year after treatment (Enloe et al. 2012). Byrd (2007) also reported a reduction in the number of viable seeds following treatment with several herbicides.

In contrast, cogongrass rhizomes are characterized by strong persistence, aggressiveness, regenerative capacity, and resistance to heat and water stress (Ayeni 1985; Eussen 1980; Shilling et al. 1997; Wilcut et al. 1988). Ayeni (1985) found a highly positive correlation of regenerative capacity of rhizomes with increasing age, weight, length, thickness, and number of visible buds. The extensive cogongrass rhizome system may comprise as much as 80% of total plant biomass, which may translate into a rhizome biomass as great as 35,867 kg ha^{-1} (16 t ac^{-1}) (Terry et al. 1997). Rhizomes form a dense mat in the upper 20 cm (7.88 in) of the profile in fine-textured soils and may reach a depth of 50 cm in sandy soils (Omezine and Harzalla 2009). These rhizome characteristics pose a challenge because elimination of all rhizome biomass is mandatory for successful eradication of cogongrass.

Given the strong regenerative and persistent nature of cogongrass rhizomes, our primary objective in this study was to determine the feasibility of cogongrass patch eradication with a focus on elimination of the entire rhizome layer. Our specific research questions included the following:

1. Can repeated annual treatments of glyphosate or imazapyr be effective for complete cogongrass rhizome elimination?
2. Does the combination of glyphosate and imazapyr improve cogongrass rhizome elimination over either herbicide alone?
3. Does the timing of annually repeated herbicide applications (spring, summer, or fall) influence the effectiveness of glyphosate, imazapyr, or both for cogongrass rhizome elimination?
4. Do repeated herbicide treatments influence energy levels or depth of surviving rhizomes?

Materials and Methods

A field study was conducted from 2008 through 2011 at locations near Tillman's Corner (30.50282° N, 88.15251° W) and Bayou La Batre (30.42500° N, 88.28835° W) in southwestern Alabama. Both locations were abandoned, open fields with near-monotypic stands of cogongrass that had not been managed for several years. Soil at the Tillman's Corner, AL, site was a Benndale sandy loam (siliceous, subactive, thermic Typic Paleudults). Soil at the Bayou La Batre, AL, site was a Troup–Heidel loamy sand (siliceous, semiactive, thermic Typic Paleudults). Soils at both locations were well drained, $>$ 1.5 m (4.92 ft) deep, and strongly acidic in reaction. The study was established at each location in a randomized complete-block design with four replications. The plot size was 9.1 by 9.1 m with a 3 m buffer around each plot that was maintained free of cogongrass with repeated glyphosate applications for the duration of the study. This was critical because cogongrass patches can expand $>$ 2 m yr^{-1} (Yager 2007), and the wide buffers eliminated the chance of rhizome encroachment from adjacent plots. Plot size was also large compared with previous cogongrass control studies (Willard et al. 1996, 1997) to allow for destructive harvesting, which occurred throughout the study. The experiment consisted of a factorial arrangement of three herbicide treatments and three application timings, resulting in nine treatments. A nontreated control was also included. Herbicide treatments were glyphosate (Accord Concentrate, Dow AgroSciences LLC, Indianapolis, IN 46268), applied at 4.48 kg ai ha^{-1}; imazapyr (Chopper Gen2, BASF, Research Triangle Park, NC 27709), applied at 0.84 kg ai ha^{-1}; and a combination of glyphosate and imazapyr at the same rates. The three application times were May, August, and October. Each herbicide treatment and timing combination was applied once a year in 2008, 2009, and 2010 to the same plots. Across all 3 yr, the spring, summer, and fall treatments were applied between May 16 to 20, July 30 to August 10, and October 5 to 12, respectively. The May glyphosate-alone treatment was modified to also include a second glyphosate treatment at the same rate each October. Methylated seed oil (Destiny HC, Winfield Solutions LLC, St. Paul, MN 55126) at 1% v/v was added to the imazapyr alone and to glyphosate plus imazapyr treatments, and a nonionic surfactant (Timberland 90, UAP, Loveland Products Inc, Loveland, CO 80632) at 0.5% v/v was added to the glyphosate treatments. At each application timing, treatments were broadcast-applied at 187 L ha^{-1} (20 gal ac^{-1}) to green, actively growing cogongrass with an all-terrain vehicle–mounted boom sprayer fitted with 11002 air induction nozzles at a pressure of 345 kPa (50.04 lb in^{-2}). Cogongrass biomass and cover at the time of each treatment varied during the course of the study. At the time of initial treatment, all plots had 80 to 100% green vegetative cover. However, cogongrass height and cover generally declined across all herbicide-treated plots during the course of the study. Although spot treatment of individual cogongrass shoots was possible because cogongrass cover declined over time, we chose to continue broadcast treatment over the entire plot to maintain complete uniformity in herbicide application. At each location, temperature and precipitation patterns generally followed historic averages during the treatment application times. The mean air temperature at the time of treatment application ranged from 21 to 27 C (69.8 to 80.6 F) for the May and October treatments and was in the low to mid 30 C range for the August treatments. In August 2009, a precipitation event of approximately 1 cm occurred approximately 3 h after treatment application. That was the only treatment time over all 3 yr that may have been influenced by precipitation within 4 h of treatment application.

Data were collected three times each year just before herbicide treatment (May, August, and October of 2008, 2009, and 2010) and in the year following the final herbicide treatments (2011). This provided comparable data for 12, 24, and 36 MAIT for each treatment, with additional growing season data in between those times. In April 2011, three replicate blocks at the Bayou La Batre, AL, site were inadvertently destroyed by the landowner, leaving only one replicate plot for each treatment.

Data collected included cogongrass rhizome biomass, maximum live-rhizome depth, rhizome TNC content, as well as cogongrass shoot biomass and visual percentage of control. Data on rhizome and shoot biomass and maximum live rhizome depth were recorded from a 0.25-m^2 (2.69-ft^2) quadrat randomly placed in each plot. Green cogongrass shoots were clipped at the ground level inside the quadrat and oven-dried at 60 C for 72 h for shoot dry

weight. Rhizome biomass was quantified by excavating a 50 by 50-cm pit beneath each quadrat to a depth of 30 cm. The bottom of each pit was closely inspected to verify that no rhizomes were present below the excavation depth. Excavated rhizomes were separated from the soil and classified as alive or dead. Rhizomes were conservatively classified as dead only if they were completely desiccated or degraded with absolutely no live tissue remaining. All live rhizomes within each quadrat, minus 15 g (0.529 oz) reserved for TNC analysis, were washed, oven-dried at 60 C for 72 h, and weighed. Visual assessments of cogongrass control for the entire plot were also made at each sampling period. Assessments, always conducted by the same observer, were made on a 0 to 100% scale, with 0% reflective of the vegetative cover of cogongrass in the nontreated control plots and 100% being elimination of all cogongrass shoots in the plot.

To quantify TNC content, a 15-g sample of healthy, white rhizomes from those harvested from each pit were placed inside a plastic freezer bag on site and stored on dry ice to prevent respiration losses during transportation. The rhizome samples were collected from horizontal sections that were previously demonstrated to have a higher TNC content than distal sections exhibiting upward curvature (S. F. Enloe, unpublished data). The rhizome samples were kept in a freezer at −20 C until analysis. TNC content was determined by using a modified version of the Shaffer-Somogyi method (Harding and Downs 1933). The method consisted of digesting 0.20 to 0.25 g of finely ground (< 1 mm [< 0.039 in]) rhizome samples with 50-ml (1.69 oz) of 0.05 N H_2SO_4 and boiling for 15 min. The samples were then cooled in a shallow ice-water bath, and 2.5 to 3.0 ml 1.0 N NaOH solution was added. The pH of the samples was maintained at 4.5 ± 0.1 while stirring using 1.0 N and 0.1 N H_2SO_4 and 1.0 N and 0.1 N NaOH. Then, 1 ml of glucoamylase enzyme solution was added, and stirring was continued. The samples were incubated for 1 h and filtered in a 250-ml volumetric flask using 541 Whatman (GE Healthcare Life Sciences, Pittsburgh, PA 15264) filter paper or glass wool. Then, 10 ml of aliquot was transferred to a test tube, and 10 ml of Shaffer-Somogyi solution was added. Samples were subsequently boiled for 15 min and cooled immediately in an ice bath. The cooled samples were treated with 2 ml of 2.5% KI and 2.5% $K_2C_2O_4.H_2O$ mixture, 10 ml of 1.0 N H_2SO_4, 0.2 ml of Fast Break defoamer (1:100; Winfield Solutions) solution, and 1 ml of 1% starch solution. Finally, the samples were titrated with 0.02 N $Na_2S_2O_3$ solution until a clear light-blue endpoint. The percentage of TNC in the rhizomes was calculated on a dry weight basis using following formula, where the sample TNC was determined by subtracting the sample titer value from the blank and enzyme TNC was the milligrams of glucoamylase enzyme used:

$$TNC\ (\%) = \{[Sample\ TNC\ (mg) - Enzyme\ TNC\ (mg)] \times 100\}/Dry\ sample\ wt\ (mg) \quad [1]$$

Statistical Analysis. Data were analyzed using generalized linear mixed models or linear mixed models methodology as implemented in SAS (SAS Institute, Cary, NC 27513) PROC GLIMMIX based on a randomized complete-block design ($r = 4$) with a split plot in time restriction on randomization. Before statistical analysis, data on shoot biomass and rhizome biomass were converted into a percentage of reduction compared with the nontreated control to adjust for variation not associated with the treatments. Visual percentage of control data were analyzed without the nontreated control values. However, the rhizome depth and TNC data were analyzed including the nontreated controls. Analyses were done using 12, 24, and 36 MAIT data. Location, treatment, MAIT, and their interactions were treated as fixed effects, whereas block within location, treatment by block within location, and MAIT by treatment by block within location were treated as random effects. The factor MAIT had a repeated-measures nature that induced a covariance relationship because of the lack of re-randomization. A heterogeneous autoregressive covariance structure [ARH (1)] was used to model the covariance relationship between observations taken from the same plot at 12, 24, and 36 MAIT. Where the location or location by treatment or both interactions were significant, the data are presented separately by location. Rhizome and shoot biomass and the percentage of visual control data were arcsine square-root transformed, but that did not change the results; therefore, nontransformed means are presented. No transformations were required for TNC and rhizome depth data. Multiple-means comparisons of significant effects were made using the *Adj = simulate* option in SAS PROC GLIMMIX at the 5% significance level.

Results and Discussion

Mean monthly air temperature and cumulative precipitation data indicated fairly typical climatic conditions throughout the study, with the exception of 2011, which was seasonally drier than average. The dry period primarily occurred during the spring in the year after the final treatments had been applied. Therefore, we do not believe that either temperature or precipitation adversely affected our treatment results during the course of the study.

Analysis of the rhizome biomass data revealed a significant location by treatment interaction ($P = 0.033$). This indicated that the efficacy of certain herbicide treatments varied by location. Within locations, there was considerable variation in rhizome biomass across sample dates in the nontreated controls (Figure 1a). At Tillman's Corner, AL,

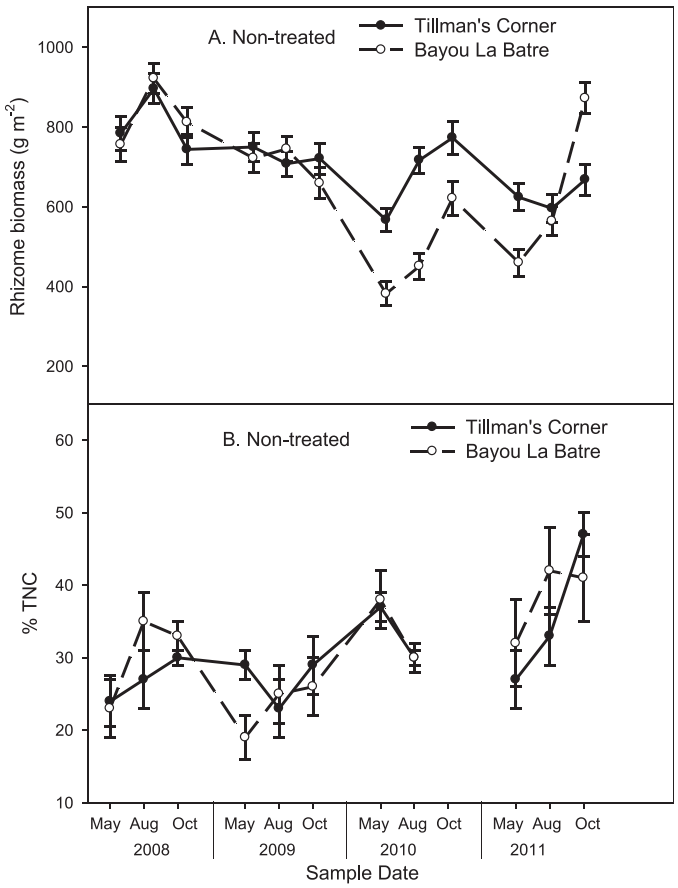

Figure 1. (a) Rhizome biomass and (b) total nonstructural carbohydrate content (TNC) in the nontreated control plots over different sample dates at Tillman's Corner, AL, and Bayou La Batre, AL, from May 2008 through October 2011. Values are mean ± SE. Location by sample date interactions for rhizome biomass and percentage of TNC were P = 0.033 and P = 0.041, respectively. TNC data were lost in October 2010 because of a sampling error.

rhizome biomass in nontreated plots fluctuated throughout the study, ranging from a low of 567 g m^{-2} (2.3 t ac^{-2}) in May 2010 to a high of 896 g m^{-2} in August 2008. Similarly, at Bayou La Batre, AL, rhizome biomass varied between 382 g m^{-2} in May 2010 to 923 g m^{-2} in August 2008. Rhizome biomass within this range has been reported in previous studies (Omezine and Harzalla 2009; Soerjani 1970). There was no consistent, seasonal pattern in rhizome biomass observed in the nontreated control plots during the first 2 sampling yr. However, rhizome biomass tended to increase between May and October at both locations in 2010 and 2011. Some temporal and spatial variation in rhizome biomass because of density-related mortality has been reported, which may explain some of the variation we observed (Reineke 1933; Yoda et al. 1963).

TNC seasonal patterns within the rhizomes in the nontreated control plots also varied across sites (P = 0.041). At Tillman's Corner, AL, there was a trend of increasing TNC levels between May and October each year (Figure 1b). The percentage of TNC values ranged from a low of 23% in the spring 2008 sampling date to nearly 50% in the fall 2011 sampling date. At Bayou La Batre, AL, there was no clear, seasonal TNC pattern. However, the range of TNC values was similar to that observed at Tillman's Corner, AL.

In contrast to rhizome biomass and TNC levels, maximum rhizome depth in the nontreated control plots remained fairly constant across locations and sample dates, with a mean maximum rhizome depth of 16 cm ± 2 SE. Previous research indicates that cogongrass rhizomes tend to occupy the upper 20 cm of the profile in fine-textured soils but may reach a depth of 50 cm in sandy soils (Omezine and Harzalla 2009).

Herbicide treatments did not result in different TNC levels (P = 0.198) or influence maximum rhizome depth (P = 0.351) of the surviving rhizomes compared with the nontreated controls. There were insufficient rhizomes to measure the percentage of TNC at 36 MAIT for any of the herbicide treatments. However, at earlier sampling dates, there were no clear differences in maximum rhizome depth or percentage of TNC in treated plots compared with the nontreated control (data not presented).

For the glyphosate treatment, there were strong differences in the rhizome biomass response to treatment timing (P = 0.001). Of the three treatment timings, the May followed by October glyphosate treatment was the only one that completely eliminated rhizome biomass within the sampled quadrats at both locations (Figures 2a and 2b). There was considerable variation in the response between locations. At Tillman's Corner, AL, for the first 2 yr, rhizome biomass decreased following the May treatment but then increased until retreatment in October (Figure 2a). Following the October treatment in the second year and the subsequent treatment in the third year, biomass declined until no live rhizomes were detected in the sampled quadrats at 36 MAIT. This was in contrast to both the August and October annual glyphosate treatments, which never reached complete rhizome elimination. Both of those treatments exhibited significant decreases in rhizome biomass during the 3-yr treatment period, but recovery was evident in the fourth year when no treatments were applied (Figure 2a). At Bayou La Batre, AL, glyphosate applied in May and October resulted in complete elimination by the second year (18 MAIT), whereas the August and October applications failed to reach rhizome elimination in the sampled quadrats at 36 MAIT (Figure 2b).

For the imazapyr treatment, there were significant differences in rhizome biomass response between locations and treatment timings early in the study. At the Tillman's Corner, AL, site at 12 MAIT, imazapyr applied in August

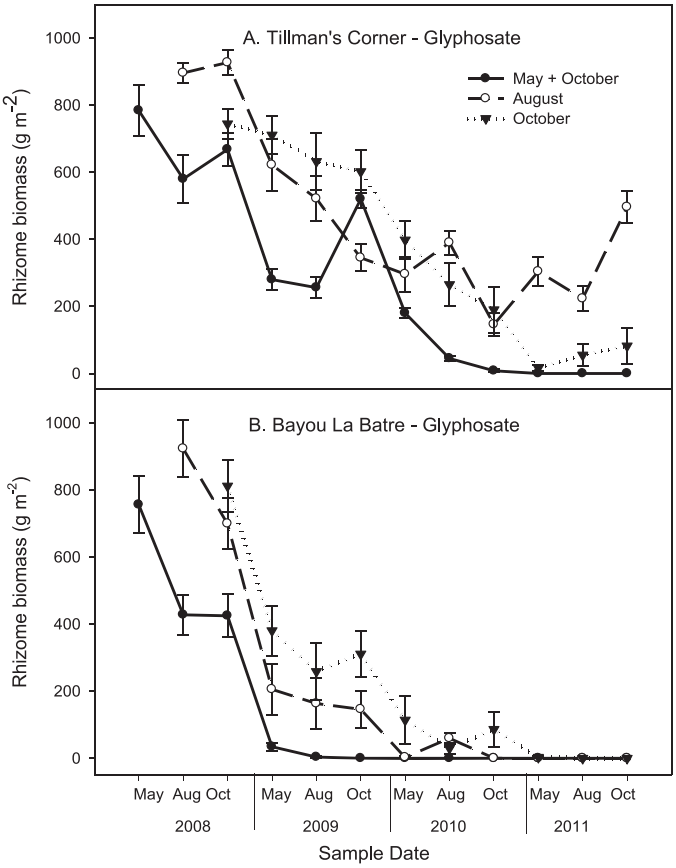

Figure 2. Rhizome biomass at (a) Tillman's Corner, AL, and (b) Bayou La Batre, AL, in glyphosate treatments from May 2008 through October 2011. Values are mean ± SE. The location by treatment by sample date interaction was significant (P = 0.001). Each line represents different glyphosate timings (May plus October, August, or October) which were applied in 2008, 2009, and 2010.

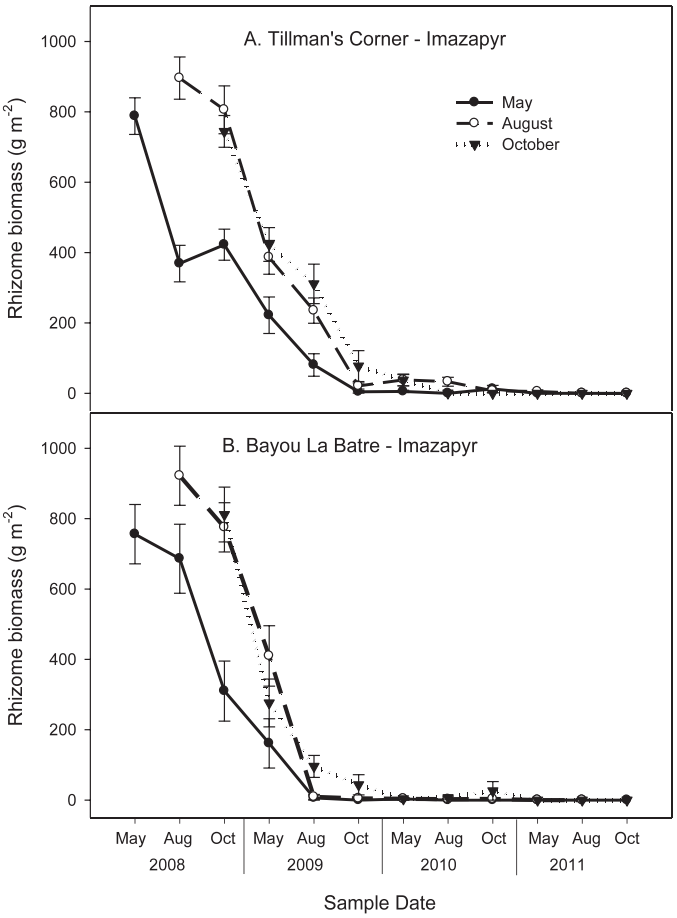

Figure 3. Rhizome biomass at (a) Tillman's Corner, AL, and (b) Bayou La Batre, AL, in imazapyr treatments from May 2008 through October 2011. Values are mean ± SE. The location by treatment by sample date interaction was significant (P = 0.001). Each line represents different imazapyr timings (May, August, or October), which were applied in 2008, 2009, and 2010.

or October decreased rhizome biomass to a greater extent than did the May imazapyr treatment (Figure 3a). At the Bayou La Batre, AL, site at 12 MAIT, imazapyr applied in August decreased rhizome biomass to a greater extent than did both the May and October treatments (Figure 3b). However, this early response may be of minor importance because rhizome biomass was nearly eliminated within the sample quadrats after two annual treatments for all treatment timings (27 MAIT) at both locations. Complete elimination of rhizome biomass in the sampled quadrats only occurred after the third year of treatment (30 MAIT).

For the glyphosate plus imazapyr treatment, the rhizome biomass response also varied between locations. At 12 MAIT, rhizome biomass was reduced to a lesser extent at Tillman's Corner, AL, than it was at Bayou La Batre, AL (Figures 4a and 4b). At the Tillman's Corner, AL, site all three treatment timings reduced rhizome biomass to a similar level (Figure 4a). However, at Bayou La Batre, AL, the August and October timings reduced rhizome biomass to a greater extent than did the May timing (Figure 4b). After two annual treatments (24 MAIT), rhizome biomass was almost completely eliminated within the sampled quadrats, except for the August timing at Tillman's Corner, AL, which had slightly higher rhizome biomass. Rhizome biomass in the sample quadrats was completely eliminated after three annual treatments (27 MAIT) for all glyphosate plus imazapyr timings.

Additional metrics were used to further evaluate whether complete elimination of cogongrass was achieved across the entire plot by each herbicide treatment (Tables 1 and 2). Reductions in cogongrass shoot biomass closely followed reductions in rhizome biomass across locations and herbicide timings (Tables 1 and 2). The only case where aboveground elimination of cogongrass was not achieved

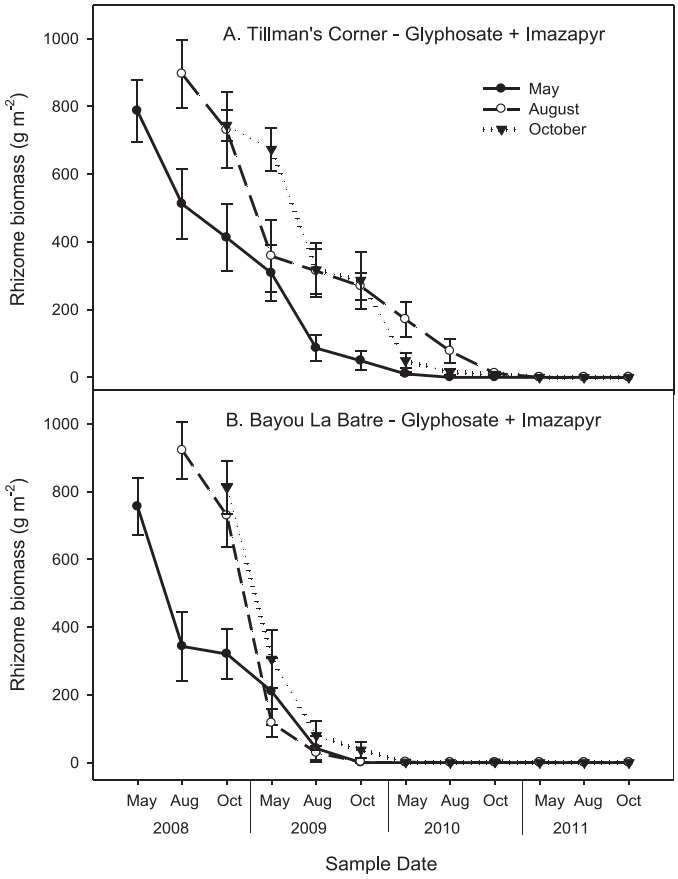

Figure 4. Rhizome biomass at (a) Tillman's Corner, AL, and (b) Bayou La Batre, AL, in glyphosate plus imazapyr treatments from May 2008 through October 2011. Values are mean ± SE. The location by treatment by sample date interaction was significant (P = 0.001). Each line represents different glyphosate plus imazapyr timings (May, August, or October), which were applied in 2008, 2009, and 2010.

along with 100% rhizome eradication within the sample quadrats was for the May imazapyr treatment at Tillman's Corner, AL. A measurement of 99% visual control indicated that cogongrass was not eradicated across entire plots (Table 1).

The combination of glyphosate plus imazapyr was not consistently more effective than imazapyr alone, at any timing. The only case of it being even slightly better was for the May application timing at Tillman's Corner, AL (Table 1). However, Willard et al. (1997) observed higher cogongrass control with sequential applications of the combination of glyphosate plus imazapyr compared with either herbicide alone.

In summary, eradication was achieved with several of the treatment–timing combinations used in this study; however, time to eradication varied by site. For example, at Tillman's Corner, AL, eradication was achieved at 36 MAIT with the May plus October glyphosate treatment (Table 1), whereas the same treatment at Bayou La Batre, AL, achieved eradication by just 18 MAIT (Table 2). For imazapyr, the May application timing at Tillman's Corner, AL, failed to eradicate cogongrass, whereas at Bayou La Batre, AL, the same treatment attained eradication in 27 MAIT. Imazapyr applied in August or October at both locations reached eradication in 33 MAIT. For glyphosate plus imazapyr, all application timings at both locations resulted in eradication 27 to 33 MAIT (Tables 1 and 2).

This is the first documented research to demonstrate complete elimination of cogongrass with these herbicides. Several previous studies reported good control of cogongrass with glyphosate, imazapyr, or a combination of the two (Minogue et al. 2012; Ramsey et al. 2003; Shilling et al. 1997; Willard et al. 1997). However, those studies generally tested herbicide treatments with one or two applications and evaluated the cogongrass response 12 to 24 MAT. In no case did those treatments result in eradication.

We demonstrated that cogongrass eradication was possible with spring, summer, or fall treatment timings when treatments were applied over 3 yr. This is in contrast to the prevailing idea that fall applications are more effective (Faircloth et al. 2005; Johnson 1999 and 2000; Miller 2007; Minogue et al. 2012; Shilling et al. 1997). Although we do not disagree with the idea of a greater effectiveness with fall treatments for cogongrass control, many land managers must pragmatically treat throughout the growing season at earlier times than fall. Our work supports the effectiveness of all treatment timings when multiple follow-up treatments are included.

Our study is unique in quantifying multiple attributes of the cogongrass rhizomes; we have found that maximum rhizome depth and percentage of TNC were not affected by repeated herbicide treatments. Finally, our research indicated significant differences in the response of cogongrass to repeated glyphosate treatments at the two locations. Similar location-related differences in response of cogongrass to foliar applications of glyphosate were reported from central Florida (Shilling et al. 1997). Although we did not quantify it, the observed differences in glyphosate efficacy at the two locations may be due to the differences in cogongrass morphology (Bryson et al. 2010) and ecotypes (Capo-chichi et al. 2008) at the two locations. Further research should examine the possible role of ecotypic differentiation across the entire southeast United States. However, it was encouraging to observe that locational differences were eventually overcome for most treatments.

In conclusion, we are not suggesting within this work that cogongrass can be eradicated from the southeastern United States. The logistics and financial requirements to do so are currently not possible. However, for land managers desiring to eradicate cogongrass within a localized

Table 1. Cogongrass response to herbicide treatments applied for 3 consecutive yr at spring, summer, or fall timings at Tillman's Corner, AL.

Herbicide	Application timing	Rhizome biomass	Shoot biomass	Visual control	Eradication achieved
		% reduction[a] 36 MAIT[b]			MAIT
Glyphosate	May plus October	100 a	100 a	100 a	36[c]
	August	63 b	58 b	51 b	—
	October	88 ab	83 ab	81 ab	—
Imazapyr	May	100 a	100 a	99 a	—
	August	100 a	100 a	100 a	33
	October	100 a	100 a	100 a	33
Glyphosate plus imazapyr	May	100 a	100 a	100 a	30
	August	100 a	100 a	100 a	33
	October	100 a	100 a	100 a	30

[a] Percentage of reduction compared with the nontreated control at 36 mo after initial treatment for each appropriate herbicide treatment by application timing.

[b] Abbreviation: MAIT, months after initial treatment for each appropriate herbicide treatment by application timing.

[c] Eradication achieved is the actual sampling date at which all cogongrass parameters reached a 100% reduction, compared with the nontreated control. "—" signifies that eradication was not achieved by 36 MAIT.

area or to "hold the line" according to the wildfire management paradigm suggested by Dewey et al. (1995), we believe that we have clearly shown that cogongrass eradication is possible with these treatments in south Alabama. Further studies should incorporate additional locations with characteristics differing from the current sites to determine the potential regional success of these approaches.

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Table 2. Cogongrass response to herbicide treatments applied for 3 consecutive yr at spring summer or fall timings at Bayou La Batre, AL.

Herbicide	Application timing	Rhizome biomass	Shoot biomass	Visual control	Eradication achieved
		% reduction[a] 36 MAIT[b]			MAIT
Glyphosate	May plus October	100 a	100 a	100 a	18[c]
	August	96 a	100 a	97 a	—
	October	98 a	100 a	98 a	—
Imazapyr	May	100 a	100 a	100 a	27
	August	100 a	100 a	100 a	33
	October	100 a	100 a	100 a	33
Glyphosate plus imazapyr	May	100 a	100 a	100 a	27
	August	100 a	100 a	100 a	33
	October	100 a	100 a	100 a	30

[a] Percentage of reduction compared with the nontreated control at 36 mo after initial treatment for each appropriate herbicide treatment by application timing.

[b] Abbreviation: MAIT, months after initial treatment for each appropriate herbicide treatment by application timing.

[c] Eradication achieved is the actual sampling date at which all cogongrass parameters reached a 100% reduction compared with the nontreated control. "—" signifies that eradication was not achieved by 36 MAIT.

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