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Dose–Response of Newly Established Elephantgrass (*Pennisetum purpureum*) to Postemergence Herbicides

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Elephantgrass has been proposed as a potential feedstock for biofuel production in south Florida. To limit future invasion of escapes in sugarcane and vegetables, the response of newly established elephantgrass to glyphosate, clethodim, sethoxydim, asulam, and trifloxysulfuron was determined using dose–response curves. Log-logistic models were used to determine the herbicide dose required to produce 90% growth reduction (GR_{90}). The GR_{90} values for shoot biomass at 21 d after treatment (DAT) were 477 g ae ha^{-1} of glyphosate, 262 g ai ha^{-1} of clethodim, 381 g ai ha^{-1} of sethoxydim, 12 kg ai ha^{-1} of asulam, and 94 g ai ha^{-1} of trifloxysulfuron. The GR_{90} values for root biomass at 35 DAT were 570 g ae ha^{-1} of glyphosate, 257 g ai ha^{-1} of clethodim, 432 g ai ha^{-1} of sethoxydim, 17 kg ai ha^{-1} of asulam, and 183 g ai ha^{-1} of trifloxysulfuron. Elephantgrass was predicted to exhibit 97, 98, 75, 1, and 5% mortality after application of glyphosate, clethodim, sethoxydim, asulam, and trifloxysulfuron, respectively, at the label use rates 35 DAT. Results suggest that glyphosate and clethodim will provide control of newly established elephantgrass at label use rates for spot treatments and in vegetables, respectively. Rates higher than the label use rate of sethoxydim will be required to provide acceptable control of newly established elephantgrass in vegetables. However, newly established elephantgrass was not controlled by asulam and trifloxysulfuron at label use rates, implying that control of escapes will be difficult in sugarcane.

Nomenclature: Asulam; clethodim; glyphosate; sethoxydim; trifloxysulfuron; elephantgrass, *Pennisetum purpureum* Schumach.; sugarcane, *Saccharum* spp. hybrids.
Key words: Bioenergy, biofuel, control, herbicides, invasive, postemergence.

Pennisetum purpureum ha sido propuesto como materia prima potencial para la producción de biocombustible en el sur de Florida. Para limitar futuras invasiones de escapes en caña de azúcar y vegetales, la respuesta de plantas recién establecidas de *P. purpureum* a glyphosate, clethodim, sethoxydim, asulam y trifloxysulfuron fue determinada usando curvas de respuesta a dosis. Modelos Log-logísticos fueron usados para determinar la dosis de herbicida requerida para producir una reducción del crecimiento del 90% (GR_{90}). Los valores de GR_{90} para la biomasa aérea a 21 d después del tratamiento (DAT) fueron 477 g ae ha^{-1} de glyphosate, 262 g ai ha^{-1} de clethodim, 381 g ai ha^{-1} de sethoxydim, 12 kg ai ha^{-1} de asulam y 94 g ai ha^{-1} de trifloxysulfuron. Los valores de GR_{90} para la biomasa radicular a 35 DAT fueron 570 g ae ha^{-1} de glyphosate, 257 g ai ha^{-1} de clethodim, 432 g ai ha^{-1} de sethoxydim, 17 kg ai ha^{-1} de asulam y 183 g ai ha^{-1} de trifloxysulfuron. Se predijo que *P. purpureum* exhibiría 97, 98, 75, 1 y 5% de mortalidad después de la aplicación de glyphosate, clethodim, sethoxydim, asulam y trifloxysulfuron, respectivamente, a las dosis de uso según las etiquetas a 35 DAT. Los resultados sugieren que glyphosate y clethodim brindarán control de plantas recién establecidas de *P. purpureum* a las dosis de uso según las etiquetas para aplicaciones localizadas y en vegetales, respectivamente. Dosis superiores a las de la etiqueta serán requeridas para que sethoxydim brinde control aceptable de plantas de *P. purpureum* recién establecidas en vegetales. Sin embargo, estas plantas no fueron controladas con asulam y trifloxysulfuron a las dosis de uso según las etiquetas, lo que implica que el control de escapes en caña de azúcar será difícil.

Perennial grasses that produce lignocellulosic biomass are generating much interest as possible feedstocks for biofuel production. Passage of the Energy Independence and Security Act of 2007 in the United States also promoted advanced biofuel production (i.e., renewable fuel other than ethanol derived from corn starch to provide a mandated 80 billion L of cellulosic ethanol by 2022). Advanced biofuel production would move the United States toward greater energy independence and security and increase production of clean renewable fuels from nontraditional crops (EISA 2007). The southeast United States, including Florida, is projected to provide 50% of advanced biofuel from feedstocks including perennial grasses, soy oil, energycane (*Saccharum spontaneum* hybrids), sweet sorghum [*Sorghum bicolor* (L.) Moench], and lodging residues (USDA 2010). As a result, elephantgrass, also called nappiergrass, has been proposed as a promising feedstock for biofuel production in south Florida.

Elephantgrass is a perennial, rhizomatous, bunch-forming, C4 grass native to tropical Africa (Coombs and Baldry 1972; Coombs et al. 1973; Holm et al. 1977) introduced as forage in the United States in 1913 (Thompson 1919). Woodard et al. (1993) recommended elephantgrass as a potential feedstock for biomass-to-energy conversion systems in Florida based on its ability to capture and convert solar energy into harvestable biomass with maximal efficiency. Similarly, Korndörfer (2011) reported that the elephantgrass variety 'Merkeron' was an appropriate feedstock for lignocellulosic ethanol and direct combustion in south Florida. Merkeron (Reg. no. 119, PI 531087) is a high-yielding hybrid between dwarf elephantgrass, no. 208, and a tall selection no. 1 (Burton 1989). Under low-input rain-fed sandy soil farming systems of south Florida Merkeron produced dry biomass yield of 26 Mg ha^{-1} (Korndörfer 2011). Additionally, south Florida has

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Table 1. Herbicide names, rates, and manufacturers.

Herbicide			
Common name	Trade name	Rate	Manufacturer
Glyphosate	Roundup PowerMax®	540 g ae/L	Monsanto Company, St. Louis, MO 63167. www.monsanto.com.
Clethodim	Select®	240 g ai/L	Winfield Solutions LLC, St. Paul, MN 55164. www.winfieldsolutionsllc.com.
Sethoxydim	Poast®	180 g ai/L	BASF Corporation, Research Triangle Park, NC 27709. www.basf.com.
Asulam	Asulox®	401 g ai/L	United Phosphorus Inc., King of Prussia, PA 19405. www.upi-usa.com.
Trifloxysulfuron	Envoke®	75% ai wt	Syngenta Crop Protection LLC, Greensboro, NC 27419. www.syngentacropprotection.com.

abundant precipitation and solar radiation throughout the year, which creates favorable climatic conditions for biomass production by elephantgrass.

However, traits deemed ideal for bioenergy crops such as high productivity, wide adaptability, and low input requirements typify many of the traits commonly associated with invasive plants (Barney and DiTomaso 2008; Raghu et al. 2006). Gordon et al. (2011) reported that elephantgrass has a high invasive potential in Florida, where it is listed as a Category I noxious weed in 29 counties (FLEPPC 2011; USDA-NRCS 2011). Thus, proposed cultivation of large hectares of elephantgrass as a biofuel feedstock in south Florida where it is found along canals, ditch banks, disturbed, and cultivated areas is raising concern among sugarcane and vegetable growers in the region. Sugarcane and vegetables are important crops grown in rotation in more than 200,000 ha (USDA 2011) in both organic and sandy soils in south Florida. The main vegetables grown in rotation with sugarcane in the region include sweet corn (*Zea mays* L.), lettuce (*Lactuca sativa* L.), and snap bean (*Phaseolus vulgaris* L.). The Presidential Executive Order 13112 specified that control measures of potential invasive plant species must be available to minimize the economic, ecological, and human health impacts that these species might cause before introduction (Presidential Documents 1999). Consequently, growers in south Florida where perennial grass introductions are planned for biomass production must have tools that they can utilize for management of escaped populations of these species in the future. Therefore, to curtail future invasion of elephantgrass escapes in sugarcane and vegetables if introduced as a biofuel feedstock in south Florida, there is need to screen available grass herbicides used in sugarcane and vegetables for its management.

Several herbicides, including glyphosate, clethodim, sethoxydim, asulam, and trifloxysulfuron, are used for perennial grass control. Glyphosate is a nonselective foliar-applied herbicide used for control of many perennial grasses (Brown et al. 1988; Ivany 1981; Richard 1997; Salisbury et al. 1991; Singh et al. 2011). Glyphosate inhibits 5-enolpyruvylshikimate-3-phosphate (EPSP) synthase, an enzyme-involved aromatic amino acid biosynthesis (Amrhein et al. 1980). Clethodim and sethoxydim are used for POST control of perennial grasses in broadleaf crops (Bedmar 1997; Grichar 1995; Ivany 1984; Ivany and Sanderson 2003; Johnson and Frans 1991; Whitwell et al. 1985). These herbicides belong to the cyclohexanedione family of herbicides, which are potent inhibitors of the enzyme acetyl-coenzyme A carboxylase, which catalyzes the first step in fatty acid biosynthesis (Burton et al. 1989; Gronwald 1994). Asulam and trifloxysulfuron herbicides are used for POST control of annual and perennial grasses in sugarcane (Dalley and Richard 2008; Hossain et al. 2001; Millhollon 1976). Asulam is a carbamate herbicide that inhibits dihydropteroate (DHP) synthase, an enzyme involved in folic acid biosynthesis, resulting in inhibition of proteins and amino acids (Stephen et al. 1980; Veerasekaran et al. 1981a,b). Trifloxysulfuron is a sulfonylurea herbicide that inhibits acetolactate synthase, an enzyme involved in the biosynthesis of three essential branched-chain amino acids (LaRossa and Schloss 1984; Ray 1984). It is unclear what the response of newly established elephantgrass would be to each of these herbicides. Therefore, the objective of this study was to evaluate the response of above- and belowground biomass of newly established elephantgrass to over-the-top application of POST herbicides using dose–response curves.

Materials and Methods

Container studies were conducted at the University of Florida Everglades Research and Education Center in Belle Glade, FL, in 2011. Merkeron stem cuttings 8 to 10 cm long with a single bud were harvested and planted in 28-cm-diam pots with a total volume of 15 L filled with Dania muck soil (Euic, hyperthermic, shallow Lithic Haplosaprists) with pH 7.5 and 75% organic matter. Pots were placed outside after planting and watered regularly to field capacity for the entire duration of the study. The experiment was repeated twice. The first and second experiments were planted on June 30 and October 6, 2011, respectively.

Forty-two days after emergence, 15 to 20-cm-tall plants were treated with five POST herbicides (Table 1). The experimental design for each herbicide was a completely randomized design with four replications. All herbicides were applied at rates ranging from 0.0625 to 4 times the label rates (Table 2). A nontreated control was included for comparison for each herbicide. Glyphosate treatments included ammoni-

Table 2. POST herbicides applied to newly established elephantgrass.

Herbicide + adjuvant[a]	Rates[b]
Glyphosate (g ae ha^{-1}) + AMS	52.5, 105, 210, 420, 840, 1,680, 3,360
Clethodim (g ai ha^{-1}) + NIS	17.5, 35, 70, 140, 280, 560, 1,120
Sethoxydim (g ai ha^{-1}) + COC	19.7, 39.4, 79, 158, 315, 630, 1,260
Asulam (kg ai ha^{-1}) + NIS	2.3, 4.6, 9.3, 18.5, 3.7, 7.4, 14.8
Trifloxysulfuron (g ai ha^{-1}) + NIS	1, 2, 4, 8, 16, 32, 64

[a] AMS, ammonium sulfate (2%, w/v); NIS, nonionic surfactant (0.25%, v/v); COC, crop oil concentrate (1%, v/v).

[b] Rates equivalent to 0.0625, 0.125, 0.25, 0.5, 1, 2, and 4 times the label use rate, respectively.

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um sulfate (S-Sul™ Sprayable Ammonium Sulfate, American Plant Food Corp., Galena, TX 77547) at 2% (v/v). Clethodim, asulam, and trifloxysulfuron treatments included nonionic surfactant (Preference®, Winfield Solutions LLC) at 0.25% (v/v), and sethoxydim treatments included crop oil concentrate (Destiny®, Winfield Solutions LLC) at 1% (v/v). Herbicide treatments were broadcast applied using a moving-nozzle spray chamber (Generation III Spray Booth, Devries Manufacturing Corp., Hollandale, MN 56045) equipped with a Teejet® XR8002VS nozzle tip (Spraying Systems Co., Wheaton, IL 60187) calibrated to deliver 180 L ha^{-1} of total volume at a pressure of 276 kPa.

Plants were harvested at soil level and dried in an oven for 48 h at 80 C to determine aboveground shoot biomass at 21 d after treatment (DAT). The binomial response of presence or absence of new elephantgrass regrowth was recorded as 1 or 0, respectively, 14 d after aboveground biomass harvesting (equivalent to 35 DAT) to determine the probability of elephantgrass resprouting (survival) after herbicide treatment. Roots were harvested from each pot and dried to determine belowground root biomass in a manner similar to shoot biomass at 35 DAT after recording of survival data. No significant interactions with experimental run were observed for each herbicide, so data were combined for analysis for each herbicide.

Analysis of variance was conducted on shoot and root biomass data to determine whether the effect of herbicide rate was significant ($P < 0.05$) using the *lme* function in R (Pinheiro and Bates 2000). Nonlinear regression analysis was then performed on shoot and root biomass data using the *drc* package of R (Ritz and Streibig 2005; R Development Core Team 2009). The four-parameter log-logistic model (Equation 1) similar to that described by Seefeldt et al. (1995) was fit to shoot and root biomass data,

$$f(x) = c + (d - c)/1 + \exp\{b[\log(x) - \log(e)]\} \quad [1]$$

where $f(x)$ is the response (shoot or root biomass), x is the herbicide rate, b is the relative slope at the inflection point, c is the lower limit, d is the upper limit, and e is the inflection point of the fitted line (equivalent to the dose required to cause 50% response).

A generalized linear model was used to conduct analysis of deviance using the *glm* function in R (Venables and Ripley 2002) for the survival data. The deviance analysis is analogous to ANOVA, in that it allows testing the data for significant effects of herbicide rate but is appropriate for the binomial nature of the survival data. After analysis of deviance, a two-parameter log-logistic model (Equation 2) was fit to the regrowth data with the *drc* package in R to determine the probability of elephantgrass survival after herbicide treatment (Odero and Gilbert 2012). The two-parameter log-logistic model is similar to Equation 1, but the upper and lower limits are constrained to 1 and 0, respectively,

$$f(x) = 1/1 + \exp\{b[\log(x) - \log(e)]\} \quad (2)$$

where $f(x)$ is the probability of elephantgrass survival and x, b, and e are the same as in Equation 1.

Results and Discussion

There were significant effects of glyphosate, clethodim, sethoxydim, asulam, and trifloxysulfuron on elephantgrass shoot and root biomass reduction at 21 and 35 DAT, respectively ($P < 0.05$). The four-parameter log-logistic model (Equation 1) provided the best fit to estimate the response of newly established elephantgrass shoot and root biomass to POST application of all the herbicides. A lack-of-fit test at the 95% level was not significant for the curves (Figures 1 to 5), indicating that the regression models were appropriate (Ritz and Streibig 2005). Similarly, there was a negative effect of all herbicides on elephantgrass survival at 35 DAT. The two-parameter log-logistic model (Equation 2) provided the best fit to estimate the probability of elephantgrass survival after POST application of all the herbicides. A lack-of-fit test at the 95% level was not significant for the curves (Figures 1 to 5), indicating that the regression models were appropriate (Ritz and Streibig 2005). Parameter estimates for Figures 1 to 5 are listed in Table 3.

Elephantgrass shoot and root biomass decreased as glyphosate rates increased (Figures 1a and 1b). The dose required to provide 90% shoot and root biomass reduction (GR_{90}) was estimated to be 477 and 570 g ae ha^{-1}, equivalent to 0.5 times and 0.6 times the label rate, respectively. Similarly, glyphosate applied at 400 and 600 g ha^{-1} provided more than 90% control of rhizomatous johnsongrass [*Sorghum halepense* (L.) Pers.] (Brown et al. 1988). The probability of elephantgrass survival decreased as glyphosate rate increased (Figure 1c). Glyphosate rate required to provide 10% probability of elephantgrass survival was predicted to be 546 g ha^{-1}, equivalent to 0.7 times the label rate. At the label glyphosate use rate of 840 g ha^{-1}, elephantgrass was predicted to exhibit 97% mortality. Our findings are similar to Camacho and Moshier (1991), who reported no significant regrowth of johnsongrass treated with glyphosate. Significant negative effect of glyphosate on root biomass and survival of elephantgrass with increasing glyphosate rates is probably related to translocation of glyphosate to belowground biomass

Table 3. Model parameters and standard errors in parenthesis for the two- and four-parameter log-logistic models (provided in Equations 1 and 2, respectively) for Figures 1–5 for newly established elephantgrass response to POST herbicides.

		Model parameters (± SE)			
Herbicide	Response	*b*	*c*	*d*	*e*
Glyphosate	Shoot biomass	1.3 (0.7)	2.5 (1.6)	17.7 (2.0)	85.8 (32.5)
	Root biomass	1.5 (0.4)	0.2 (0.5)	8.4 (0.7)	129.3 (27.6)
	Survival	2.8 (0.9)	—	—	249.4 (43.9)
Clethodim	Shoot biomass	1.2 (0.5)	2.8 (1.7)	17.6 (1.7)	39.0 (15.0)
	Root biomass	0.9 (0.5)	1.0 (1.1)	9.5 (0.9)	22.0 (10.2)
	Survival	2.0 (0.6)	—	—	40.0 (8.8)
Sethoxydim	Shoot biomass	1.4 (0.9)	4.1 (2.1)	17.0 (2.1)	79.8 (39.6)
	Root biomass	1.2 (0.4)	1.4 (0.8)	8.8 (0.7)	69.9 (24.5)
	Survival	2.6 (0.7)	—	—	204.8 (37.7)
Asulam	Shoot biomass	0.8 (0.6)	4.9 (5.1)	21.4 (2.3)	0.8 (0.8)
	Root biomass	0.9 (0.6)	1.9 (1.9)	7.3 (0.8)	1.4 (1.4)
	Survival	3.3 (1.6)	—	—	14.6 (3.0)
Trifloxysulfuron	Shoot biomass	0.7 (0.8)	6.8 (7.3)	19.2 (2.4)	4.7 (9.9)
	Root biomass	0.7 (0.7)	2.6 (4.3)	8.8 (1.1)	9.4 (21.1)
	Survival	2.3 (1.0)	—	—	72.3 (24.7)

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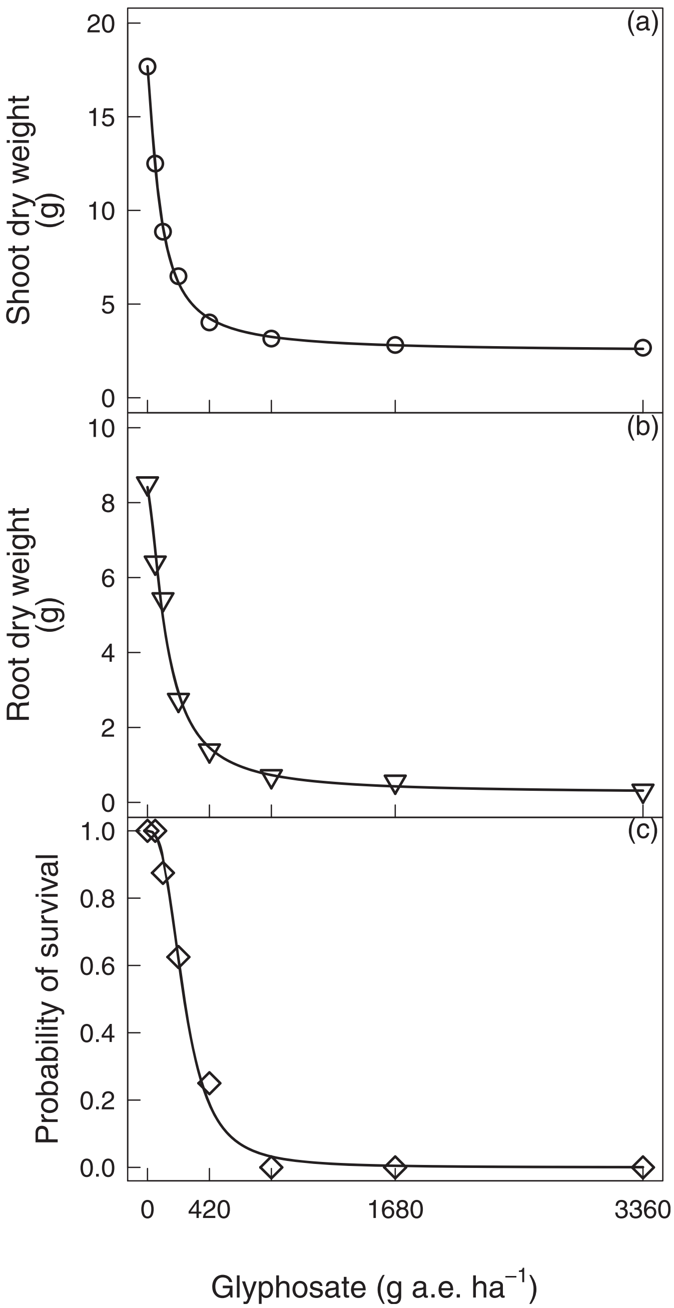

Figure 1. (a) Shoot biomass of newly emerged elephantgrass in response to glyphosate at 21 d after treatment (DAT). (b) Root biomass of newly emerged elephantgrass in response to glyphosate at 35 DAT. (c) Probability of survival of glyphosate-treated newly emerged elephantgrass 14 d after aboveground biomass harvesting (equivalent to 35 DAT). Model parameters are reported in Table 3.

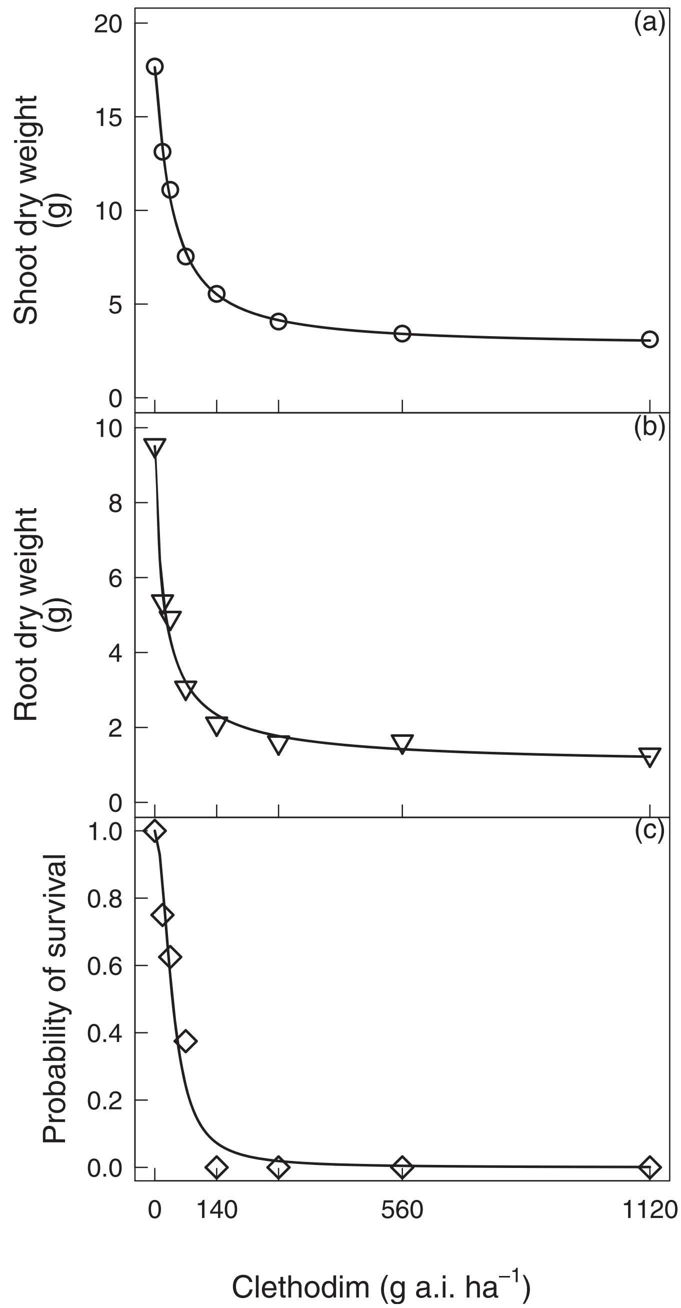

Figure 2. (a) Shoot biomass of newly emerged elephantgrass in response to clethodim at 21 d after treatment (DAT). (b) Root biomass of newly emerged elephantgrass in response to clethodim at 35 DAT. (c) Probability of survival of clethodim-treated newly emerged elephantgrass 14 d after aboveground biomass harvesting (equivalent to 35 DAT). Model parameters are reported in Table 3.

of elephantgrass. Absorbed glyphosate has been reported to readily translocate to belowground biomass of similar rhizomatous johnsongrass (Camacho and Moshier 1991; McWhorter et al. 1980) and quackgrass [*Elymus repens* (L.) Gould] (Claus and Behrens 1976).

Shoot and root biomass of elephantgrass decreased as clethodim rates increased (Figures 2a and 2b). The GR_{90} values for shoot and root biomass reduction were estimated to be 262 and 257 g ai ha^{-1}, respectively, which is equivalent to 0.9 times the label rate. Other researchers have reported varying control of perennial rhizomatous grasses with clethodim. For example, Johnson and Frans (1991) reported that two sequential applications of clethodim at 70 g ai ha^{-1} provided up to 99% control of johnsongrass in soybeans [*Glycine max* (L.) Merr.]. However, Bedmar (1997) reported that 336 g ha^{-1} of clethodim provided 94% bermudagrass

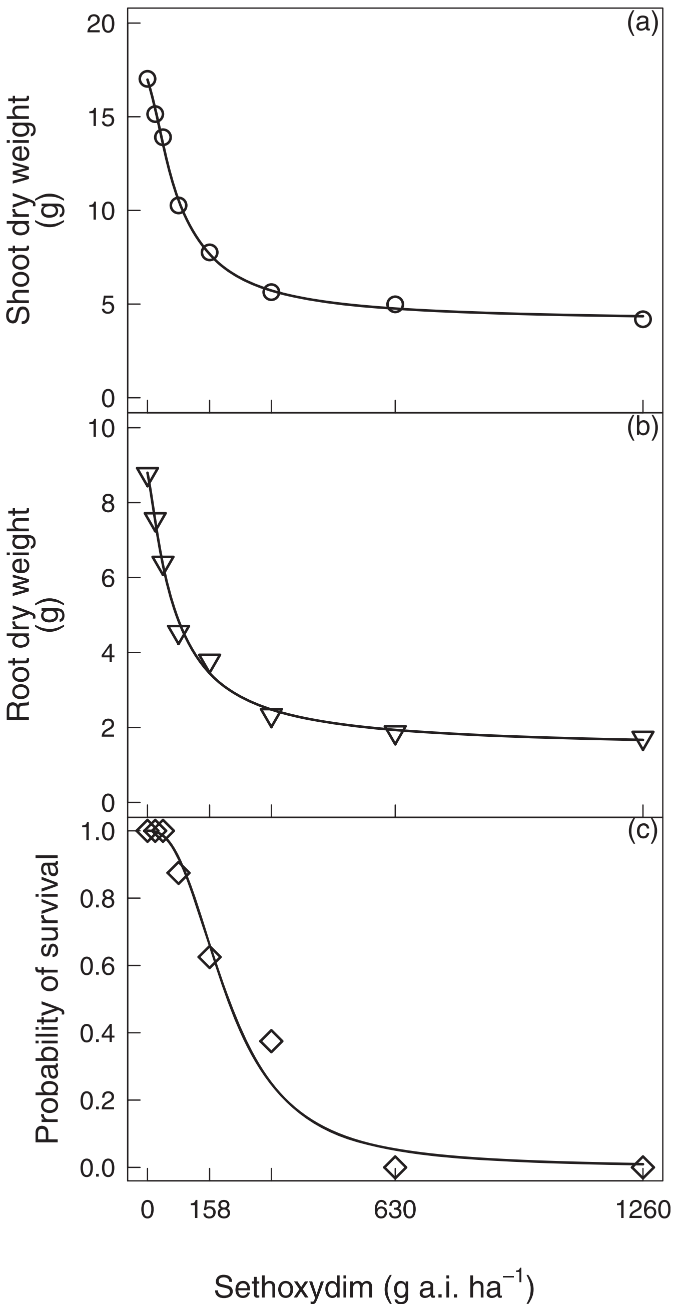

Figure 3. (a) Shoot biomass of newly emerged elephantgrass in response to sethoxydim at 21 d after treatment (DAT). (b) Root biomass of newly emerged elephantgrass in response to sethoxydim at 35 DAT. (c) Probability of survival of sethoxydim-treated newly emerged elephantgrass 14 d after aboveground biomass harvesting (equivalent to 35 DAT). Model parameters are reported in Table 3.

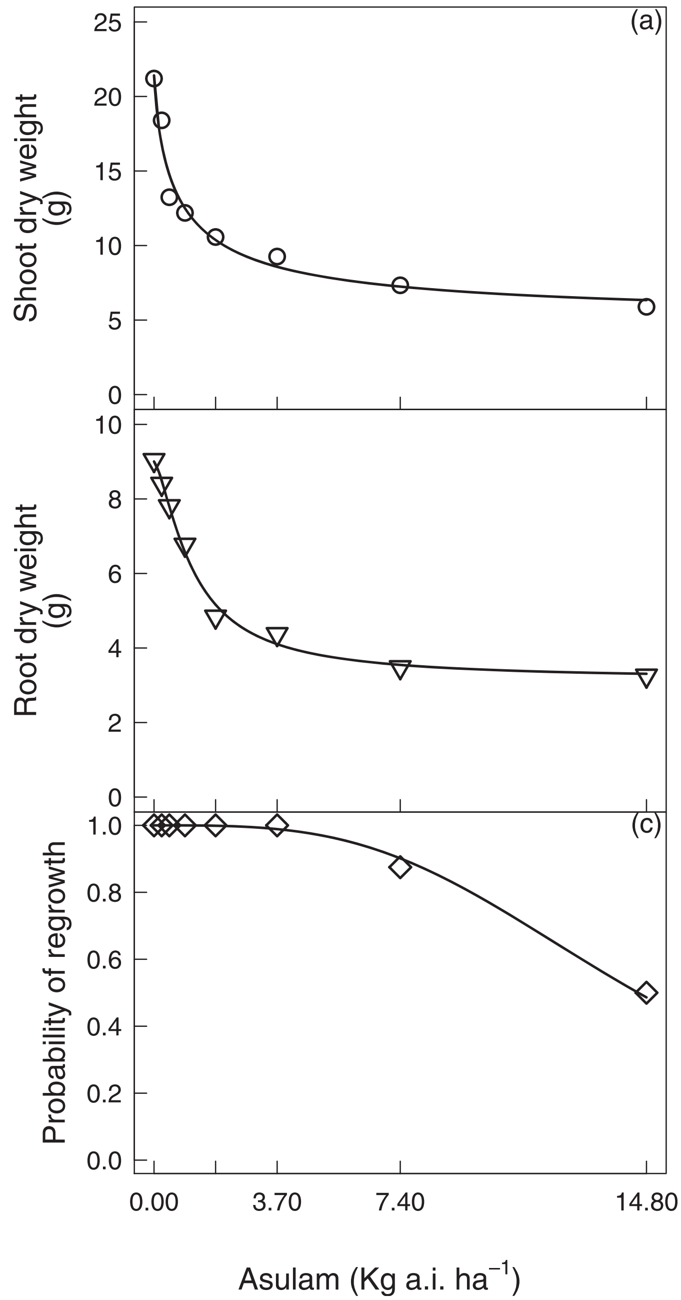

Figure 4. (a) Shoot biomass of newly emerged elephantgrass in response to asulam at 21 d after treatment (DAT). (b) Root biomass of newly emerged elephantgrass in response to asulam at 35 DAT. (c) Probability of survival of asulam-treated newly emerged elephantgrass 14 d after aboveground biomass harvesting (equivalent to 35 DAT). Model parameters are reported in Table 3.

[*Cynodon dactylon* (L.) Pers.] biomass reduction in soybean. Elephantgrass survival decreased as clethodim rate increased (Figure 2c). Clethodim rate required to provide 10% probability of elephantgrass survival was predicted to be 118 g ha^{-1}, equivalent to 0.4 times the label rate. The mortality of elephantgrass was predicted to be 98% at the labeled clethodim use rate of 280 g ha^{-1}. The decreased probability of elephantgrass survival with increasing rates of clethodim confirms the observed root biomass reduction. It is unclear how much clethodim translocated out of the treated elephantgrass leaves to the roots. This is because Nandula et al. (2007) reported that most of the clethodim remained in the treated leaf of bermudagrass and the amount that translocated out of the treated leaf remained in the shoot. In their study, a negligible amount translocated to bermudagrass roots. Despite the report, our study shows that

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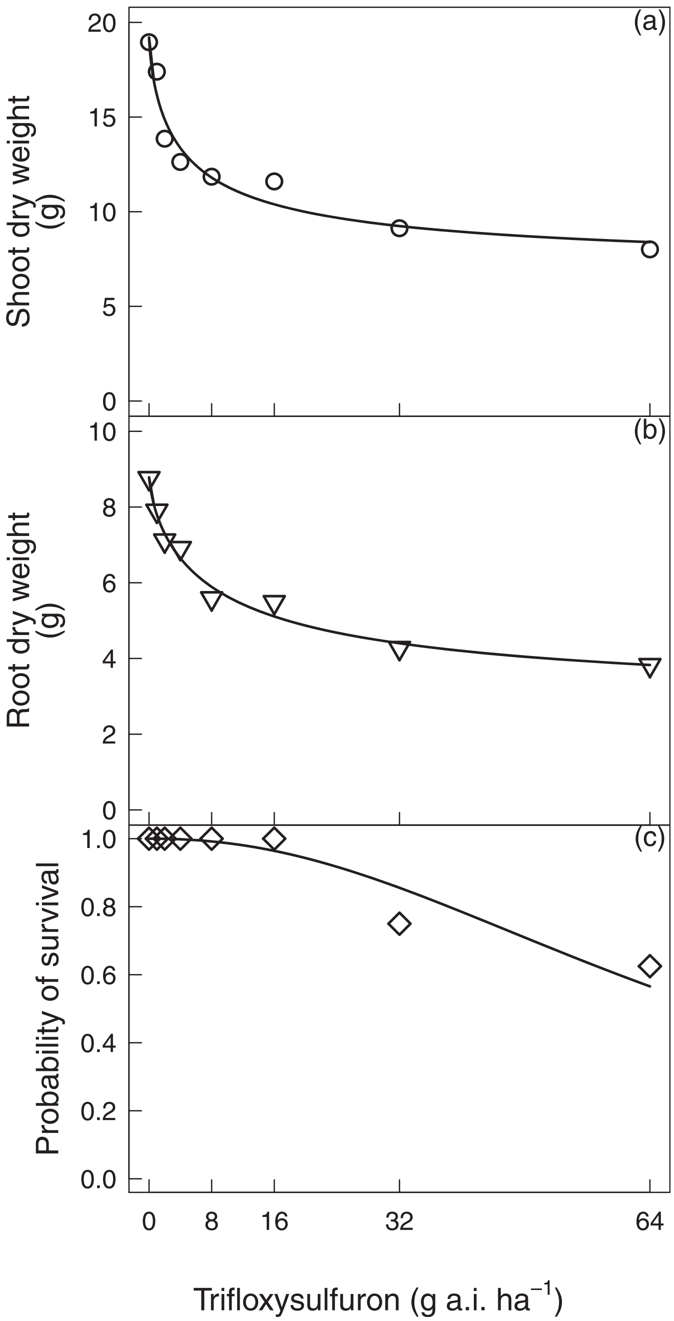

Figure 5. (a) Shoot biomass of newly emerged elephantgrass in response to trifloxysulfuron at 21 d after treatment (DAT). (b) Root biomass of newly emerged elephantgrass in response to trifloxysulfuron at 35 DAT. (c) Probability of survival of trifloxysulfuron-treated newly emerged elephantgrass 14 d after aboveground biomass harvesting (equivalent to 35 DAT). Model parameters are reported in Table 3.

clethodim will result in both above- and belowground biomass reduction of newly established elephantgrass.

Both elephantgrass shoot and root biomass decreased as sethoxydim rates increased (Figures 3a and 3b). The GR_{90} values for shoot and root biomass reduction were estimated to be 381 and 432 g ai ha^{-1}, equivalent to 1.2 times and 1.4 times the label rate, respectively. In soybean, a single application of sethoxydim at 300 g ha^{-1} provided up to 86% control of rhizomatous johnsongrass (Whitwell et al. 1985). However, a single application of sethoxydim at 210 g ha^{-1} failed to control bermudagrass ($<$ 60%) in soybean (Grichar 1995). Similarly, a single application of sethoxydim at 310 g ha^{-1} controlled $<$ 35% of bermudagrass in peanut (Wilcut 1991). Wills (1984) also reported 36% control of bermudagrass with sethoxydim at 280 g ha^{-1}. Previous studies have reported $<$ 2% translocation of sethoxydim from treated leaves to roots of bermudagrass, goosegrass [*Eleusine indica* (L.) Gaertn.], and centipedegrass [*Eremochloa ophiuroides* (Munro) Hack] (McCarty et al. 1990; Wills 1984), probably explaining our observed results. Elephantgrass survival decreased as the sethoxydim rate increased (Figure 3c). The sethoxydim rate required to provide 10% probability of elephantgrass survival was predicted to be 483 g ha^{-1}, equivalent to 1.5 times the label rate. Elephantgrass was predicted to exhibit 75% mortality at the labeled sethoxydim use rate of 315 g ha^{-1}.

Elephantgrass shoot and root biomass decreased as asulam rates increased (Figures 4a and 4b). The GR_{90} values for shoot and root biomass reductions were predicted to be 12 and 17 kg ai ha^{-1}, respectively, equivalent to 3.3 times and 4.5 times the label rate, respectively. Odero and Gilbert (2012) reported a maximum 50% shoot biomass reduction of rhizomatous giant reed (*Arundo donax* L.) in the greenhouse at an asulam rate of 7.4 kg ha^{-1} at 21 DAT. In the field, giant reed shoot biomass was reduced by a maximum of 43% at 42 DAT. Previous research has shown that asulam provides between 51 to 79% control of johnsongrass (Dalley and Richard 2008; Millhollon 1976). Elephantgrass survival decreased as rate of asulam increased (Figure 4c). The asulam rate required to provide 10% probability of elephantgrass survival was predicted to be 28 kg ha^{-1}, equivalent to 7.5 times the label rate. At the maximum labeled asulam use rate of 3.7 kg ha^{-1}, elephantgrass was predicted to exhibit 1% mortality. Despite reports of asulam accumulation in roots of wild oat (*Avena fatua* L.) and rhizomes of bracken fern (*Pteridium aquilinum* L. Kuhn) after foliar application (Sharma et al. 1978; Veerasekaran et al. 1977), the present study indicates that very high rates of asulam are required to result in reduction of elephantgrass root biomass.

Shoot and root biomass of elephantgrass decreased as trifloxysulfuron rates increased (Figures 5a and 5b). The GR_{90} values for shoot and root biomass reductions were predicted to be 94 and 183 g ai ha^{-1}, respectively, equivalent to 5.9 times and 11.4 times the label rate, respectively. Trifloxysulfuron applied at 7.4 kg ha^{-1} in the greenhouse resulted in 50% shoot biomass reduction of giant reed at 21 DAT (Odero and Gilbert 2012). In the field, giant reed shoot biomass was reduced by a maximum of 43% at 42 DAT (Odero and Gilbert 2012). Similarly, trifloxysulfuron has been reported to provide 42% control of johnsongrass (Dalley and Richard 2008; Millhollon 1976). Survival of elephantgrass decreased as the rate of trifloxysulfuron increased (Figure 5c). The trifloxysulfuron rate required to provide 10% probability of elephantgrass survival was predicted to be 198 g ha^{-1}, equivalent to 12.4 times the label rate. At the label

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trifloxysulfuron use rate of 16 g ha^{-1}, elephantgrass was predicted to exhibit 5% mortality. Minor translocation of foliar-applied trifloxysulfuron to the roots and newly formed rhizomes of green kyllinga (*Kyllinga gracillima* L.) and false-green kyllinga (*K. brevifolia* Rottb.) has been reported (McElroy et al. 2004), probably explaining the limited effect of trifloxysulfuron on root biomass and survival of elephantgrass observed. Similarly, Troxler et al. (2003) reported that neither yellow nutsedge (*Cyperus rotundus* L.) nor purple nutsedge (*C. esculentus* L.) translocated more than 4% of foliar-applied trifloxysulfuron to the tubers and roots. Additionally, most foliar-applied ALS-inhibiting herbicides such as trifloxysulfuron have been reported not to translocate out of the treated leaves of many broadleaf plant species (Askew and Wilcut 2002; Wilcut et al. 1989). The absence of effect of trifloxysulfuron at very high rates on root biomass and mortality of elephantgrass could be attributed in part to limited translocation to belowground biomass.

The results from this study showed that glyphosate and clethodim will be effective in controlling newly established elephantgrass for spot treatments and vegetable production, respectively, at the labeled rate of 840 and 280 g ha^{-1}, respectively. More than the label rate of sethoxydim of 315 g ha^{-1} will be required to provide acceptable control of newly established elephantgrass in vegetable production. However, label use rates of trifloxysulfuron and asulam of 16 g ha^{-1} and 2.8 to 3.7 kg ha^{-1}, respectively, will not provide control of newly established elephantgrass in sugarcane. Thus, high doses of asulam and trifloxysulfuron will be required to provide control of newly established elephantgrass. Application of these herbicides will not be within the label use rate and would exacerbate sugarcane injury. These results show that the long-term containment of an aggressively spreading elephantgrass would be difficult if they escaped and became established in sugarcane with currently available selective sugarcane grass herbicides.

Literature Cited

Amrhein, N., B. Deus, P. Gehrke, and H. C. Steinrucken. 1980. The site of the inhibition of the shikimate pathway by glyphosate. II. Interference of glyphosate with chorismate formation in vivo and in vitro. Plant Physiol. 66:830–834.

Askew, S. D. and J. W. Wilcut. 2002. Absorption, translocation, and metabolism of foliar-applied trifloxysulfuron in cotton, peanut, and selected weeds. Weed Sci. 50:293–298.

Barney, J. N. and J. M. DiTomaso. 2008. Nonnative species and bioenergy: are we cultivating the next invader? BioScience 58:64–70.

Bedmar, F. 1997. Bermudagrass (*Cynodon dactylon*) control in sunflower (*Helianthus annuus*), soybean (*Glycine max*), and potato (*Solanum tuberosum*) with postemergence graminicides. Weed Technol. 11:683–688.

Brown, S. M., J. M. Chandler, and J. E. Morrison, Jr. 1988. Glyphosate for johnsongrass (*Sorghum halepense*) control in no-till sorghum (*Sorghum bicolor*). Weed Sci. 36:510–513.

Burton, G. W. 1989. Registration of 'Merkeron' nappiergrass. Crop Sci. 29:1327.

Burton, J. D., J. W. Gronwald, D. A. Somers, B. G. Gengenbach, and D. L. Wyse. 1989. Inhibition of corn acetyl-CoA carboxylase by cyclohexanedione and aryloxyphenoxypropionate herbicides. Pestic. Biochem. Phys. 34:76–85.

Camacho, R. F. and L. J. Moshier. 1991. Absorption, translocation, and activity of CGA-136872, DPX-V9360, and glyphosate in rhizome johnsongrass (*Sorghum halepense*). Weed Sci. 39:354–357.

Claus, J. S. and R. Behrens. 1976. Glyphosate translocation and quackgrass rhizome bud kill. Weed Sci. 24:149–152.

Coombs, J. and C. W. Baldry. 1972. C-4 pathway in *Pennisetum purpureum*. Nat. New Biol. 238:268–270.

Coombs, J., C. W. Baldry, and C. Bucke. 1973. The C-4 pathway in *Pennisetum purpureum* II. Malate dehydrogenase and malic enzyme. Planta 110:109–120.

Dalley, C. D. and E. P. Richard, Jr. 2008. Control of rhizome johnsongrass (*Sorghum halepense*) in sugarcane with trifloxysulfuron and asulam. Weed Technol. 22:397–401.

[EISA] Energy Independence and Security Act. 2007. Public Law 110-140-Energy Independence and Security Act of 2007. U.S. Government Printing Office. http://www.gpo.gov/fdsys/pkg/PLAW-110publ140/content-detail.html. Accessed: December 1, 2011.

[FLEPPC] Florida Exotic Pest Plant Council. 2011. List of Invasive Plant Species. Florida Exotic Pest Plant Council. Wildland Weeds 14:11–14. http://www.fleppc.org/list/11list.html. Accessed December 1, 2011.

Gordon, D. R., K. J. Tancig, D. A. Onderdonk, and C. A. Gantz. 2011. Assessing the invasive potential of biofuel species proposed for Florida and the United States using the Australian Weed Risk Assessment. Biomass Bioenerg. 35:74–79.

Grichar, W. J. 1995. Comparison of postemergence herbicides for common bermudagrass (*Cynodon dactylon*) control in peanut (*Arachis hypogaea*). Weed Technol. 9:825–828.

Gronwald, J. W. 1994. Herbicides inhibiting acetyl-CoA carboxylase. Biochem. Soc. Trans. 22:616–621.

Holm, L. G., D. L. Plucknett, J. V. Pancho, and J. P. Herberger. 1977. The World's Worst Weeds: Distribution and Biology. Honolulu: University Press of Hawaii. Pp. 367–372.

Hossain, A. M., H. Kuramochi, Y. Ishimine, and H. Akamine. 2001. Application timing of asulam for torpedograss (*Panicum repens* L.) control in sugarcane in Okinawa island. Weed Biol. Manag. 1:108–114.

Ivany, J. A. 1981. Quackgrass (*Agropyron repens*) control with fall-applied glyphosate and other herbicides. Weed Sci. 29:382–386.

Ivany, J. A. 1984. Quackgrass (*Agropyron repens*) control in potatoes (*Solanum tuberosum*) with sethoxydim. Weed Sci. 32:194–197.

Ivany, J. A. and J. B. Sanderson. 2003. Quackgrass (*Elytrigia repens*) control in potatoes (*Solanum tuberosum*) with clethodim. Phytoprotection 84:27–35.

Johnson, W. G. and R. E. Frans. 1991. Johnsongrass (*Sorghum halepense*) control in soybeans (*Glycine max*) with postemergence herbicides. Weed Technol. 5:87–91.

Korndörfer, P. H. 2011. Biomass and Energy Yields of Bioenergy Germplasm Grown on Sandy Soils in Florida. M.S. thesis. Gainesville, FL: University of Florida. 80 p.

LaRossa, R. A. and J. V. Schloss. 1984. The herbicide sulfometuron methyl is bacteriostatic due to inhibition of acetolactate synthase. J. Biol. Chem. 259:8753–8757.

McCarty, L. B., J. M. Higgins, F. T. Corbin, and T. Whitwell. 1990. Absorption, translocation, and metabolism of sethoxydim in centipedegrass and goosegrass. J. Am. Soc. Hortic. Sci. 115:605–607.

McElroy, J. S., F. H. Yelverton, I. C. Burke, and J. W. Wilcut. 2004. Absorption, translocation, and metabolism of halosulfuron and trifloxysulfuron in green kyllinga (*Kyllinga brevifolia*) and false-green kyllinga (*K. gracillima*). Weed Sci. 52:704–710.

McWhorter, C. G., T. N. Jordan, and G. D. Wills. 1980. Translocation of ^{14}C-glyphosate in soybeans (*Glycine max*) and johnsongrass (*Sorghum halepense*). Weed Sci. 28:113–118.

Millhollon, R. W. 1976. Asulam for johnsongrass control in sugarcane. Weed Sci. 24:496–499.

Nandula, V. K., D. H. Poston, K. N. Reddy, and C. H. Koger. 2007. Formulation and adjuvant effects on uptake and translocation of clethodim in bermudagrass (*Cynodon dactylon*). Weed Sci. 55:6–11.

Odero, D. C. and R. A. Gilbert. 2012. Response of giant reed (*Arundo donax*) to asulam and trifloxysulfuron. Weed Technol. 26:71–76.

Pinheiro, J. C. and D. M. Bates. 2000. Mixed-Effects Models in S and S-PLUS. Springer-Verlag. New York. 530 p.

Presidential Documents. 1999. Executive Order 13112 on February 3, 1999. Invasive Species. Federal Register Vol. 64. No. 25. http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=1999_register&docid=99-3184-filed.pdf. Accessed: January 28, 2012.

R Development Core Team. 2009. R: A Language and Environment for Statistical Computing. Vienna. ISBN 3-900051-07-9. URL: http://www.R-project.org.

Raghu, S., R. C. Anderson, C. C. Daehler, A. S. Davis, R. N. Wiedenmann, D. Simberloff, and R. N. Mack. 2006. Adding biofuels to the invasive species fire? Science 313:1742.

Ray, T. B. 1984. Inhibition of valine and isoleucine biosynthesis in plants. Plant Physiol. 75:827–831.

Richard, E. P. 1997. Effects of fallow bermudagrass (*Cynodon dactylon*) control programs on newly planted sugarcane (*Saccharum* spp. hybrids). Weed Technol. 11:677–682.

Ritz, C. and J. C. Streibig. 2005. Bioassay analysis using R. J. Stat. Soft. 12:1–22.

Salisbury, C. D., J. M. Chandler, and M. G. Merkle. 1991. Ammonium sulfate enhancement of glyphosate and SC-0224 control of johnsongrass (*Sorghum halepense*). Weed Technol. 5:18–21.

Seefeldt, S. S., J. E. Jensen, and E. P. Fuerst. 1995. Log-logistic analysis of herbicide dose–response relationships. Weed Technol. 9:218–227.

Sharma, M. P., W. H. Van Den Born, and D. K. McBeath. 1978. Spray retention, foliar penetration, translocation and selectivity of asulam in wild oats and flax. Weed Res. 18:169–173.

Singh, M., M. Malik, A.H.M. Ramirez, and A. J. Jhala. 2011. Tank mix of saflufenacil with glyphosate and pendimethalin for broad-spectrum weed control in Florida citrus. HortTechnology 21:606–615.

Stephen, N. H., G. T. Cook, and H. J. Duncan. 1980. A possible mechanism of action of asulam involving folic acid biosynthesis. Ann. Appl. Biol. 96:227–234.

Thompson, J. B. 1919. Napier and Merker Grasses. Gainsville, FL: Florida Agricultural Experiment Station Bulletin 153. Pp. 235–249.

Troxler, S. C., I. C. Burke, J. W. Wilcut, W. D. Smith, and J. Burton. 2003. Absorption, translocation, and metabolism of foliar-applied trifloxysulfuron in purple and yellow nutsedge (*Cyperus rotundus* and *C. esculentus*). Weed Sci. 51:13–18.

[USDA] United States Department of Agriculture. 2010. A USDA Regional Roadmap to Meeting the Biofuels Goals of the Renewable Fuels Standard by 2022. http://www.usda.gov/documents/USDA_Biofuels_Report_6232010.pdf. Accessed January 28, 2012.

[USDA] United States Department of Agriculture. 2011. National Agricultural Statistics Service. Statistics by Subject. http://www.nass.usda.gov/Statistics_by_Subject/index.php?sector=CROPS. Accessed: January 28, 2012.

[USDA-NRCS] United States Department of Agriculture-Natural Resources Conservation Service. 2011. County Distribution *Pennisetum purpureum* Schumach—Elephant Grass PEPU2 in the state of Florida. http://plants.usda.gov/java/county?state_name=Florida&statefips=12&symbol=PEPU2. Accessed: December 1, 2011.

Veerasekaran, P., R. C. Kirkwood, and W. W. Fletcher. 1977. Studies on the mode of action of asulam in bracken (*Pteridium aquilinum* L. Kuhn) I. Absorption and translocation of [14C]asulam. Weed Res. 17:33–39.

Veerasekaran, P., R. C. Kirkwood, and E. W. Parnell. 1981a. Studies of the mechanism of action of asulam in plants. Part I: antagonistic interaction of asulam and 4-amino-benzoic acid. Pestic. Sci. 12:325–329.

Veerasekaran, P., R. C. Kirkwood, and E. W. Parnell. 1981b. Studies of the mechanism of action of asulam in plants. Part II: effect of asulam on the biosynthesis of folic acid. Pestic. Sci. 12:330–338.

Venables, W. N. and B. D. Ripley. 2002. Modern Applied Statistics with S. 4th ed. New York: Springer. 495 p.

Whitwell, T., G. Wehtje, R. H. Walker, and J. A. McGuire. 1985. Johnsongrass (*Sorghum halepense*) control in soybeans (*Glycine max*) with postemergence grass herbicides applied alone and in mixtures. Weed Sci. 33:673–678.

Wilcut, J. W. 1991. Efficacy and economics of common bermudagrass (*Cynodon dactylon*) control in peanut (*Arachis hypogaea*). Peanut Sci. 18:106–109.

Wilcut, J. W., G. R. Wehtje, M. G. Patterson, T. A. Cole, and T. V. Hicks. 1989. Absorption, translocation, and metabolism of foliar-applied chlorimuron in soybeans (*Glycine max*), peanuts (*Arachis hypogaea*), and selected weeds. Weed Sci. 37:175–180.

Wills, G. D. 1984. Toxicity and translocation of sethoxydim in bermudagrass (*Cynodon dactylon*) as affected by environment. Weed Sci. 32:20–24.

Woodard, K. R., G. M. Prine, and S. Bachrein. 1993. Solar energy recovery by elephantgrass, energycane, and elephantmillet canopies. Crop Sci. 33:824–830.

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