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Response of Energycane to Preemergence and Postemergence Herbicides

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Energycane has been proposed as a potential, perennial bioenergy crop for lignocellulosic-derived fuel production in the United States. Herbicides currently used in sugarcane and other crops can potentially be used in energycane if there is acceptable tolerance. Also, to limit future invasion of energycane escapes, herbicides used for perennial grass control could potentially be used for management of escapes. In container studies conducted outside, aboveground and belowground biomass of energycane was measured to evaluate energycane tolerance to 9 PRE and 19 POST herbicides used in sugarcane and other crops. PRE application of atrazine, diuron, mesotrione, metribuzin, pendimethalin, and *S*-metolachlor at rates labeled for sugarcane did not significantly injure ($< 3\%$) or reduce energycane biomass compared with the nontreated plants 28 and 56 d after treatment (DAT). Injury from clomazone (54%), flumioxazin (7%), and hexazinone (29%) was observed 28 DAT. Injury from flumioxazin was transient and was not observed at 56 DAT. At 56 DAT, energycane injury increased to 71 and 98%, respectively, for clomazone and hexazinone. Hexazinone and clomazone applied PRE significantly reduced biomass compared with the nontreated plants. At 28 DAT, POST application of 2,4-D amine, ametryn, asulam, atrazine, carfentrazone, dicamba, halosulfuron, mesotrione, metribuzin, and trifloxysulfuron at labeled rates for sugarcane did not injure or significantly reduce energycane biomass compared with the nontreated plants. Injury was observed when clethodim (99%), clomazone (51%), diuron (51%), flumioxazin (21%), glufosinate (84%), glyphosate (100%), hexazinone (100%), paraquat (66%), and sethoxydim (100%) were applied POST, and each of these treatments reduced energycane biomass compared with the nontreated plants. These results show that several PRE and POST herbicides used for weed management in sugarcane may potentially be used in energycane for weed control. Also, based on our results, clethodim, glyphosate, and sethoxydim would be effective for management of energycane escapes.

Nomenclature: Ametryn; asulam; atrazine; carfentrazone; clethodim; clomazone; 2,4-D amine; dicamba; diuron; flumioxazin; glufosinate; glyphosate; halosulfuron; hexazinone; mesotrione; metribuzin, paraquat; *S*-metolachlor; sethoxydim; trifloxysulfuron; energycane, *Saccharum* spp. × *Saccharum spontaneum* 'UFCP 78-1013′, 'UFCP 82-1655′; sugarcane, *Saccharum officinarum* L.

Key words: Bioenergy crop, herbicide injury, herbicide tolerance.

La caña energética ha sido propuesta como un cultivo bioenergético potencial para la producción de combustibles lignocelulósicos en los Estados Unidos. Los herbicidas usados actualmente en caña de azúcar y otros cultivos pueden ser potencialmente usados en caña energética si la tolerancia es aceptable. También, para limitar invasiones producto de escapes de caña energética, los herbicidas usados para el control de gramíneas perennes podrían potencialmente ser usados para el manejo de estos escapes. Estudios con potes fueron realizados a la intemperie, en donde se midió la biomasa de la caña energética sobre y dentro del suelo para evaluar la tolerancia a 9 herbicidas PRE y 19 herbicidas POST usados en caña de azúcar y otros cultivos. La aplicación PRE de atrazine, diuron, mesotrione, metribuzin, pendimethalin, y *S*-metolachlor a dosis de etiqueta para caña de azúcar no causaron un daño significativo ($<3\%$) ni redujeron la biomasa de la caña energética al compararse con plantas sin tratamiento, a 28 y 56 días después del tratamiento (DAT). El daño causado por flumioxazin fue transitorio y no se observó a 56 DAT. A 56 DAT, el daño en la caña energética aumentó a 71 y 98%, respectivamente, para clomazone y hexazinone. Hexazinone y clomazone aplicados PRE redujeron significativamente la biomasa al compararse con las plantas sin tratamiento. A 28 DAT, aplicaciones POST de 2,4-D amine, ametryn, asulam, atrazine, carfentrazone, dicamba, halosulfuron, mesotrione, metribuzin, y trifloxysulfuron a las dosis de etiqueta para caña de azúcar no dañaron o redujeron significativamente la biomasa de la caña energética en comparación con las plantas testigo. Se observó daño cuando se aplicó POST clethodim (99%), clomazone (51%), diuron (51%), flumioxazin (21%), glufosinate (84%), glyphosate (100%), hexazinone (100%), paraquat (66%), y sethoxydim (100%), y cada uno de estos tratamientos redujo la biomasa de la caña energética en comparación con las plantas sin tratamiento. Estos resultados pueden ser potencialmente usados en el control de malezas en caña energética. También, con base en nuestros resultados, clethodim, glyphosate, y sethoxydim podrían ser efectivos para el manejo de escapes de caña energética.

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Concerns with climate change, growing energy demand, and energy security have led to increased interest in alternative renewable energy derived from lignocellulosic biomass (Ragauskas et al. 2006). Energycane may be an acceptable feedstock for lignocellulosic biomass production (Fedenko et al. 2013), thus contributing to the need for advanced biofuels outlined by the U.S. Department of Agriculture (USDA 2010). These biofuels are one of the many promising renewable energy alternatives to fossil-based fuels needed to achieve energy independence and to reduce the impact on global climate (EISA 2007; Farrell et al. 2006; Ragauskas et al. 2006). In addition, biofuels from lignocellulosic biomass, including perennial species, may be more ecologically friendly than grain feedstocks (Groom et al. 2008). As a result, investments in research and development of advanced biofuel technology, including high-biomass energycane cultivars, have increased during the past several years in the United States.

Energycane is a perennial crop derived from interspecific crossing of sugarcane (*Saccharum* spp. hybrids) with clones from wild sugarcane relatives (*Saccharum spontaneum* L.), resulting in cultivars that produce narrow stalks with low sucrose, higher fiber, higher stalks per hectare, greater dry biomass yields, increased stand longevity, better disease and pest resistance, and better cold tolerance, compared with conventional sugarcane (Knoll et al. 2013; León et al. 2010; Wang et al. 2008). For example, energycane clones in Florida recorded 37% higher leaf-area index and 65% more stalks per unit area in comparison with commercial sugarcane cultivars (León et al. 2010). Energycane has been reported to have high dry matter yields of up to 53 Mg ha^{-1} yr^{-1}, depending on location and cultivar, in tropical and subtropical climates (Bischoff et al. 2008; Knoll et al. 2012, 2013; Mislevy et al. 1995; Woodard and Prine 1993). High dry-matter yields of energycane in tropical and subtropical regions are due to a long growing period as apical meristems in tillers continue growth throughout the year, thereby enabling the plant to maintain light interception and radiation-use efficiency at high levels over an extended period (Woodard et al. 1993). The high productivity and adaptability of energycane makes it an ideal bioenergy feedstock.

There are two types of energycane classified based on sugar, fiber components, and intended uses (Tew and Cobill 2008). Type I energycane is selected and cultivated to maximize both sugar and fiber components for production of lignocellulosic biomass in addition to sugar for ethanol production. In contrast, type II is selected and cultivated solely for its fiber content for lignocellulosic biomass production. It was not until 2007 that 'L 79-1002', a high-fiber energycane cultivar, was released in the United States (Bischoff et al. 2008). Although L 79-1002 showed promising energy characteristics, it also showed increased susceptibility to sugarcane smut disease (*Ustilago scitaminea* Sydow & P. Sydow) in the main sugarcane growing areas of Louisiana and Florida. As a result, new high-yielding, disease-free germplasm was needed. Recently, the U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS) Sugar Research Unit, in Houma, LA, released energycane cultivars 'HoCP 91-552' (Tew et al. 2011), 'Ho 00-961' (White et al. 2011), and 'Ho 02-113' (Hale et al. 2012) for commercial production in Louisiana. However, the genetic diversity in energycane is still very low compared with other crops, particularly in Florida, where there have been no previous cultivar releases. Consequently, a cooperative energycane selection program was established in 2007 between University of Florida and USDA-ARS Sugarcane Field Station in Canal Point, FL, to produce high-yielding and disease-resistant energycane germplasm (Sandhu 2014). Since inception of the program, high-fiber energycane cultivars 'UFCP 78-1013' and 'UFCP 82-1655' were released in 2013 for cultivation on marginal soils in Florida (Sandhu 2014). One of the main considerations in the breeding program in Florida was to develop energycane cultivars that could be grown in marginal mineral soils with low fertility not commonly used for sugarcane production. These mineral soils are primarily Spodosols and Entisols with low organic matter (0.5 to 3%) and insignificant clay or silt content (McCray et al. 2014).

There are several herbicides, including 2,4-D amine, asulam, atrazine, carfentrazone, clomazone, dicamba, diuron, flumioxazin, halosulfuron, hexazinone, mesotrione, metribuzin, pendimethalin, *S*-metolachlor, and trifloxysulfuron, currently used in conventional sugarcane (Bhullar et al. 2012; Correia et al. 2012; Dalley and Richard 2008; Judice et al. 2006; Richard and Dalley 2006), which can

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potentially be used in energycane if there is acceptable crop tolerance. Because differential tolerance and sensitivity of other crops, such as corn (*Zea mays* L.), to herbicides have been reported (Diebold et al. 2004; Green 1998; Grey et al. 2000; O'Sullivan and Sikkema 2002; Widstrom and Dowler 1995; Williams et al. 2005), energycane tolerance to sugarcane herbicides needs to be evaluated to provide potential growers with options for selective weed control if planted hectares increase in the future in the southeast United States. In addition, because energycane would be grown in rotation with vegetables, including sweet corn and snap bean (*Phaseolus vulgaris* L.), information is needed on management of future escapes in rotational crops and fallow sugarcane fields. Herbicides, including clethodim, glufosinate, glyphosate, and sethoxydim, used for perennial grass control could potentially be used for management of energycane escapes. Therefore, the objective of this study was to evaluate the tolerance of energycane to several PRE and POST herbicides.

Materials and Methods

PRE Experiment. Energycane cultivars UFCP 78-1013 and UFCP 82-1655 stalks were harvested from a first-ratoon nursery at the Everglades Research and Education Center (EREC) in Belle Glade, FL (26.66°N, 80.63°W) in 2014. The harvested stalks were cut into 7- to 10-cm segments with a single, viable bud and were planted approximately 7.6 cm deep in 2.36-L pots containing Holopaw fine sand (loamy, siliceous, active, hyperthermic Grossarenic Endoaqualfs), with a pH 7.5 and 1.6% organic matter, collected from a grower field near Loxahatchee, FL (26.80°N, 80.42°W). Four stalk segments were planted per pot before spraying with PRE herbicides on the same day as they were planted.

Treatments consisted of a factorial arrangement of nine herbicides (Table 1) and two energycane cultivars in a completely randomized design with four replications. Each herbicide was applied PRE at labeled (1×) and twice labeled (2×) rates for sugarcane, with the exception of *S*-metolachlor, which is not labeled for use in sugarcane in the United States, and was applied at 1× and 2× rates for corn. A nontreated control was included for comparison. 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} at 276 kPa. Pots were irrigated with 20 mm of water immediately after spraying to incorporate the herbicides into the soil, and each pot was placed in 51 by 25 by 5-cm nonperforated flat and placed outside for the entire duration of the study. Ten grams of 14–14–14 slow-release fertilizer (Osmocote Smart-Release Plant Food, Scotts-Sierra Horticultural Products Company, Marysville, OH 43040) was added to each pot at 14 d after planting. The pots were then subirrigated as needed for the duration of the study to ensure that moisture was not a limiting factor. The experiment was conducted twice. The first and second experimental runs were sprayed on February 5, 2013, and March 11, 2014, respectively.

Energycane shoots began to emerge in each pot at 14 d after planting. Visual estimation of herbicide injury was determined at 28 and 56 d after treatment (DAT) on a scale of 0 (no injury) to 100 (no green tissue or plant death). Following the last evaluation, shoots were harvested at the soil level, and roots were washed to remove soil for aboveground and belowground biomass, respectively. Harvested biomass was dried in an oven for 72 h at 60 C to determine dry weight.

Data were subjected to ANOVA using the GLM procedure in SAS software (version 9.3; SAS Institute Inc. Cary, NC 27513) to determine the significance of herbicide treatment, cultivar, experimental run effects, and interactions. Means were compared with the untreated control using a one-tailed Dunnett test ($P \leq 0.05$). Spearman rank-order correlation between injury and biomass accumulation was determined using the CORR procedure in SAS at $P \leq 0.05$.

POST Experiment. Energycane cultivars UFCP 78-1013 and UFCP 82-1655 stalks were harvested in 2014 at the EREC, similar to methods used in the PRE experiment, and were cut into segments with one viable bud. Harvested stalk segments were planted in 51 by 25 by 5 cm flats containing a commercial potting medium (Fafard mixes for professional use, Conrad Fafard Inc., Agawan, MA 01001). The flats were placed in a greenhouse under natural light and set at a maximum temperature of

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Table 1. Herbicide names, manufacturer, and timing of application.

Herbicide	Trade name	Manufacturer	Timing of application
Pendimethalin	Prowl H_2O	BASF Corporation, Research Triangle, NC (http://www.agro.basf.com)	PRE
S-metolachlor	Dual II Magnum	Syngenta Crop Protection LLC, Greensboro, NC (http://www.syngentacropprotection.com)	PRE
Atrazine	Atrazine 4L	Winfield Solutions LLC, St. Paul, MN (http://www.winfield.com)	PRE and POST
Clomazone	Command 3ME	FMC Corporation Agricultural Products Group, Philadelphia, PA (http://www.fmccrop.com)	PRE and POST
Diuron	Direx 4L	Makhteshim Agan of North America, Inc., Raleigh, NC (http://www.manainc.com/products)	PRE and POST
Flumioxazin	Valor SX	Valent U.S.A. Corporation, Walnut Creek, CA (http://www.valent.com)	PRE and POST
Hexazinone	Velpar DF	DuPont Crop Protection, Wilmington, DE (http://www.dupont.com)	PRE and POST
Mesotrione	Callisto	Syngenta	PRE and POST
Metribuzin	Metribuzin 75	Loveland Products Inc., Greeley, CO (http://www.lovelandproducts.com)	PRE and POST
2,4-D amine	Amine 4 2,4-D Weed Killer	Loveland	POST
Ametryn	Evik DF	Syngenta	POST
Asulam	Asulox	United Phosphorus, Inc., King of Prussia, PA (http://www.upi-usa.com)	POST
Carfentrazone	Aim EC	FMC	POST
Clethodim	Select 2EC	Valent	POST
Dicamba	Clarity	BASF	POST
Glufosinate	Finale	Bayer Crop Science LP, Research Triangle Park, NC (http://www.cropscience.bayer.com)	POST
Glyphosate	Roundup PowerMax	Monsanto Company, St. Louis, MO (http://www.monsanto.com)	POST
Halosulfuron	Sandea	Gowan Company, Yuma, A (http://www.gowanco.com)	POST
Paraquat	Gramoxone Inteon	Syngenta	POST
Sethoxydim	Poast	BASF	POST
Trifloxysulfuron	Envoke	Syngenta	POST

33 C and irrigated as needed. At 21 d after shoot emergence, plants were transplanted into 2.36 L pots. The pots were filled with Holopaw, fine sand mixed with 10 g of 14–14–14 slow-release fertilizer and placed outside for the remainder of the experiment. Each pot contained one transplant. The plants were allowed to grow in the pots for 2 wk after transplanting to ensure that they overcame transplant shock caused by the change in the environment from the flats to the pots before herbicide application. Two weeks after transplanting, POST herbicide treatments were applied to plants averaging 36 and 46 cm in height for the first and second experimental runs, respectively. The greater growth in the second experimental run was probably attributed to extended periods of day length compared with the first experimental run. Growth increases have been observed in Florida for grasses because of extended photoperiod (Sinclair et al. 2003).

Treatments consisted of a factorial arrangement of 19 herbicides (Table 1), most with labeled uses in sugarcane, applied POST at 1× and 2× use rates, and two energycane cultivars in a completely randomized design with four replications. Herbicide treatments were applied in a manner similar to the PRE experiment, and plants were placed outside after herbicide application for the entire duration of the study. Nonionic surfactant (Preference, Winfield Solutions, LLC, St. Paul, MN 55164), crop oil concentrate (Prime Oil, Winfield Solutions, LLC., St. Paul, MN 55164), or ammonium sulfate (S-Sul sprayable ammonium sulfate, American Plant Food Corp., Galena, TX 77547) were used as adjuvants as

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Table 2. Energycane injury and dry biomass after PRE herbicide application.[a]

Treatment	Rate	Injury 28 DAT[b]	Injury 56 DAT	Dry biomass[c] Aboveground	Dry biomass[c] Belowground
	kg ai ha^{-1}	%	%	g	g
Nontreated control	—	0	0	3.0	2.6
Atrazine	4.5	0	0	3.1	2.5
	9.0	0	0	2.7	1.9
Clomazone	1.89	54*	71*	1.4*	1.0*
	3.8	72*	95*	0.6*	0.6*
Diuron	3.36	1	0	2.5	1.7
	6.7	3	8*	1.8*	1.6*
Flumioxazin	0.286	7*	0	2.9	2.1
	0.57	10*	0	2.7	1.7
Hexazinone	1.12	29*	89*	0.6*	0.2*
	2.24	37*	98*	0.4*	0.1*
Metribuzin	2.24	0	0	2.5	1.9
	4.5	0	0	2.5	1.7
Mesotrione	0.27	0	0	2.8	2.3
	0.54	0	0	3.6	2.8
Pendimethalin	4.47	0	0	2.8	2.4
	8.9	0	0	3.3	2.4
S-metolachlor	1.79	0	0	3.0	3.0
	3.57	0	0	3.0	1.9

[a] Data averaged across experiments and cultivars. Means followed by an asterisk (*) within a column are significantly different from the nontreated check using the Dunnett's test at P = 0.05.

[b] Abbreviation: DAT, d after treatment.

[c] Plants harvested 56 d after treatment to determine aboveground and belowground dry biomass.

directed by the herbicide label. The experiment was conducted twice. The first and second experimental runs were treated with herbicides on April 4 and 24, 2014, respectively.

Injury from the treatments was evaluated visually at 28 DAT on a scale of 0 (no injury) to 100 (no green tissue or plant death). Aboveground and belowground biomass was harvested at 28 and 36 DAT for the first and second experimental runs, respectively. Harvested biomass was dried in a manner similar to the PRE experiment. Data analysis was performed separately for each experimental run to determine the significance of the herbicide treatment, cultivar effects, and interactions in a manner similar to the PRE experiment. Data were analyzed separately for each experimental run because of different plant sizes at herbicide application and different harvest timing.

Results and Discussion

PRE Experiment. There were no significant interactions among the experimental run, cultivar, or treatment; therefore, data were combined over cultivars and runs. Atrazine, mesotrione, metribuzin, pendimethalin, and *S*-metolachlor applied PRE did not injure energycane by 28 or 56 DAT, regardless of application rate (Table 2), suggesting that energycane exhibited tolerance to these herbicides. PRE applications of pendimethalin, atrazine, and metribuzin alone or in combination are widely used for selective weed control in sugarcane (Jones and Griffin 2009; Judice et al. 2006; Millhollon 1993; Richard 1989), most likely explaining why these herbicides did not injure energycane. Mesotrione can be applied PRE in sugarcane after planting of plant-cane or after harvest of ratoon-cane for broad-spectrum, residual broadleaf-weed control (Anonymous 2009). Mesotrione is also labeled for use in the spring as a POST treatment in sugarcane. Although *S*-metolachlor is labeled for use in sugarcane in other countries, such as Brazil and Australia (Correia et al. 2012), it is not so labeled in the United States, and the results of this study suggested that energycane was tolerant to that herbicide.

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Diuron applied at 1× and 2× rates did not injure energycane at 28 DAT; however, the injury observed at 56 DAT at 2× rate was enough to reduce biomass production (Table 2). At 28 DAT, flumioxazin, hexazinone, and clomazone application injured energycane 7, 29, and 54%, respectively, at the 1× rate and 10, 37, and 72% at the 2× rate. Energycane injury varied by herbicide but generally consisted of severe bleaching of leaf tissue for clomazone and browning followed by death from hexazinone. However, injury from flumioxazin was transient and was not observed by 56 DAT at either application rates. Richard and Dalley (2006) reported no visible injury on sugarcane 6 wk after treatment from PRE application of flumioxazin at 0.28 and 0.42 kg ha^{-1}. Injury to energycane at 56 DAT increased to 71 and 98% with treatments containing hexazinone and clomazone, respectively. Sugarcane cultivars have previously shown extreme sensitivity to hexazinone, particularly in the plant–cane crop (Richard 1989), which is similar to the response observed by energycane in the present study.

Herbicide-induced injury was negatively correlated with aboveground ($r = -0.49$, $P < 0.01$) and belowground ($r = -0.48$, $P < 0.01$) biomass of energycane at 28 DAT. Also, at 56 DAT, there was a negative correlation between herbicide injury and aboveground ($r = -0.59$, $P < 0.01$) and belowground ($r = -0.58$, $P < 0.01$) biomass of energycane. Biomass, aboveground and belowground, similar to the injury ratings, was not reduced by atrazine, mesotrione, metribuzin, pendimethalin, or *S*-metolachlor treatments compared with the nontreated plants (Table 2). This demonstrated that energycane was highly tolerant to these PRE herbicides. Clomazone and hexazinone at both rates significantly reduced aboveground and belowground biomass compared with the nontreated control because of the observed severe injury. Richard (1989) reported up to 86% sugarcane yield reduction in cultivars extremely sensitivity to hexazinone. Only the 2× rate of diuron resulted in significant reduction in aboveground and belowground biomass compared with the nontreated control. Results of our study showed that diuron was not significantly different from the nontreated control with respect to energycane injury and biomass at the 1× rate, implying that it can be safely used at the labeled sugarcane rate.

POST Experiment. Because POST herbicide treatments were applied to energycane at different heights and harvested at different timings for the two experimental runs, data were analyzed separately for each run. There was no significant interaction between cultivar and treatment for either study; therefore, data were combined over cultivars for analysis. All rates of clethodim, glyphosate, hexazinone, and sethoxydim resulted in complete energycane death (Tables 3 and 4). Similarly, the highest (2×) rate of diuron, glufosinate, and paraquat resulted in complete energycane death. The 1× rate of each of these herbicides resulted in 44 to 84% energycane injury. Injury included chlorosis of leaf tissue, wilting, desiccation, and necrosis of leaves and the entire plant. These results show that hexazinone cannot be used over-the-top on energycane for POST weed control, whereas graminicides (clethodim, sethoxydim) and glyphosate can potentially be used to control newly established energycane escapes in vegetables and fallow sugarcane fields, respectively. In addition, the graminicides and glyphosate can potentially be used for spot treatment of energycane escapes in sugarcane. However, more than the labeled rate of glufosinate and paraquat is required to provide complete control of newly established energycane escapes in fallow sugarcane fields or as spot treatments in sugarcane. Sugarcane is extremely sensitive to glyphosate (Richard 1991) and fluazifop-P (Richard 1991, 1995), an acetyl CoA carboxylase (ACCase) inhibitor, which may explain the observed injury on energycane from glyphosate and ACCase inhibitors clethodim and sethoxydim. Inability of perennial grasses to recover from significant injury caused by glyphosate, clethodim, and sethoxydim has been reported previously (Lingenfelter and Curran 2007; Rankins et al. 2005). Griffin et al. (2004) reported 25% injury of ratoon sugarcane at 28 DAT in a field study, which declined to 8% at 56 DAT following paraquat application at 0.7 kg ha^{-1}. Because foliar-applied paraquat remains in the treated leaf, ratoon sugarcane with extensive underground reserves can rapidly initiate new growth after desiccation of sugarcane foliage by paraquat (Griffin et al. 2004). In contrast, injury observed on energycane in our potted study from paraquat at 0.56 kg ha^{-1} was up to 66% at 28 DAT, probably because of lack of extensive underground reserves in newly established

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Table 3. Energycane injury and dry biomass 28 d after POST herbicide treatment application for the first experimental run.[a,b]

Treatment	Rate	Injury	Dry biomass	
			Aboveground	Belowground
	kg ai ha^{-1}	%	g	
Nontreated control		0	6.1	5.9
2,4-D amine[c]	2.24	0	6.7	6.5
	4.5	0	6.4	5.9
Ametryn + NIS	1.33	0	6.3	6.7
	2.65	8	5.7	5.6
Asulam + NIS	3.74	0	6.4	6.7
	7.5	5	6.7	6.5
Atrazine	4.5	0	5.8	6.6
	9.0	0	6.4	5.9
Carfentrazone + NIS + AMS	0.0166	0	6.2	6.2
	0.0333	0	6.5	6.0
Clethodim + COC	0.14	99*	0.9*	1.3*
	0.28	99*	0.7*	0.5*
Clomazone + NIS	1.89	51*	4.3	1.1*
	3.8	74*	3.2*	0.8*
Dicamba[c] + NIS	0.84	0	6.1	6.8
	1.68	0	6.3	6.7
Diuron + NIS	1.68	51*	3.5*	2.5*
	3.36	99*	0.8*	0.5*
Flumioxazin + NIS	0.143	21*	3.5*	2.8*
	0.286	33*	3.3*	2.7*
Glufosinate + AMS	0.45	84*	1.8*	0.6*
	0.9	100*	1.5*	0.2*
Glyphosate[c]	0.84	100*	1.3*	1.4*
	1.68	100*	1.1*	0.5*
Halosulfuron + NIS	0.07	0	6.7	6.1
	0.14	0	5.8	6.5
Hexazinone + NIS	1.12	100*	0.8*	0.4*
	2.24	100*	1.0*	0.4*
Mesotrione + NIS + AMS	0.105	0	6.0	6.0
	1.02	0	6.6	6.0
Metribuzin	2.24	0	6.0	4.3
	4.5	10*	4.4	3.6*
Paraquat	0.56	66*	1.7*	0.6*
	1.12	99*	0.5*	0.2*
Sethoxydim + COC	0.32	100*	1.0*	1.1*
	0.64	100*	1.1*	0.6*
Trifloxysulfuron + NIS	0.0158	6	6.0	5.4
	0.0315	10*	4.5	3.2*

[a] Abbreviations: NIS, nonionic surfactant at 0.25% v/v; COC, crop oil concentrate at 1% v/v; AMS, ammonium sulfate at 1.8% w/v.

[b] Data averaged across cultivars. Means followed by an asterisk (*) within a column are significantly different from the nontreated check using the Dunnett's test at $P = 0.05$.

[c] Herbicide rates are listed in kg ae ha^{-1}.

energycane (equivalent to plant cane crop) compared with a ratoon crop. In addition, the root-bound conditions in our potted study may have resulted in greater injury than that experienced in the field.

Clomazone caused 51 to 74% injury on energycane, exhibited as foliar bleaching, at both rates of application (Tables 3 and 4). Diuron at 1× rate resulted in 44 to 51% energycane injury. Although diuron is widely used in sugarcane, it can cause

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Table 4. Energycane injury at 28 d after POST herbicide treatment application and dry biomass at 36 d after POST herbicide treatment application for the second experimental run.[a,b]

			Dry biomass	
Treatment	Rate	Injury	Aboveground	Belowground
	kg ai ha^{-1}	%	g	
Nontreated control		0	16.2	12.7
2,4-D amine[c]	2.24	0	16.4	10.8
	4.5	0	12.8	10.4
Ametryn + NIS	1.33	0	14.0	10.8
	2.65	8*	16.0	10.0
Asulam + NIS	3.74	0	13.6	9.8
	7.5	0	11.0	10.1
Atrazine	4.5	0	13.6	11.1
	9.0	0	15.4	11.1
Carfentrazone + NIS + AMS	0.0166	0	14.3	10.8
	0.0333	0	10.5	7.4
Clethodim + COC	0.14	100*	0.8*	3.9*
	0.28	100*	1.1*	1.5*
Clomazone + NIS	1.89	54*	9.3	4.3*
	3.8	66*	4.1*	2.0*
Dicamba[c] + NIS	0.84	0	18.4	11.6
	1.68	0	16.8	10.6
Diuron + NIS	1.68	44*	4.3*	2.9*
	3.36	100*	1.2*	0.3*
Flumioxazin + NIS	0.143	27*	5.7*	3.5*
	0.286	38*	5.2*	3.15*
Glufosinate + AMS	0.45	59*	2.4*	1.8*
	0.9	100*	1.4*	1.1*
Glyphosate[c]	0.84	100*	1.8*	1.7*
	1.68	100*	1.1*	0.6*
Halosulfuron + NIS	0.07	0	13.5	11.4
	0.14	0	11.4	10.3
Hexazinone + NIS	1.12	100*	2.1*	0.3*
	2.24	100*	1.4*	0.3*
Mesotrione + NIS + AMS	0.105	0	15.9	12.2
	1.02	0	14.4	12.0
Metribuzin	2.24	0	10.4	9.9
	4.5	8*	8.0*	6.5*
Paraquat	0.56	63*	3.9*	2.1*
	1.12	99*	2.0*	2.4*
Sethoxydim + COC	0.32	100*	1.6*	2.2*
	0.64	100*	1.4*	3.3*
Trifloxysulfuron + NIS	0.0158	7*	15.7	11.3
	0.0315	11*	12.6	9.2

[a] Abbreviations: NIS, nonionic surfactant at 0.25% v/v; COC, crop oil concentrate at 1% v/v; AMS, ammonium sulfate at 1.8% w/v.

[b] Data averaged across cultivars. Means followed by an asterisk (*) within a column are significantly different from the nontreated check using the Dunnett's test at $P = 0.05$.

[c] Herbicide rates are listed in kg ae ha^{-1}.

injury to the crop. For example, application of diuron at 2.13 kg ha^{-1} to four-leaf ratoon sugarcane approximately 31 cm tall resulted in 15 and 3% sugarcane injury at 28 and 56 DAT, respectively (Griffin et al. 2004). Energycane injury from flumioxazin was 21 to 38% and included reddening and necrosis following POST application at both rates. Richard and Dalley (2006) reported injury on sugarcane of up to 40% from POST application of flumioxazin at 0.28 kg ha^{-1}. In sugarcane, injury

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from flumioxazin can be minimized by using POST-directed sprays rather than over-the-top applications (Richard and Dalley 2006). These results show that clomazone, diuron, and flumioxazin cannot be used as over-the-top or POST-directed herbicides in energycane for weed control because of risk of severe injury.

Injury from trifloxysulfuron and asulam, herbicides labeled for POST control of annual and perennial weeds in sugarcane was 0 to 5% and 6 to 11%, respectively, at both application rates (Tables 3 and 4). Observed injury included yellowing and reddening of leaves from asulam and trifloxysulfuron, respectively. Dalley and Richard (2008) reported that trifloxysulfuron and asulam alone or in combination caused less than 10% injury to sugarcane up to 10 wk after treatment. Atrazine, carfentrazone, mesotrione, 2,4-D amine, dicamba, and halosulfuron did not cause any visible injury symptoms regardless of application rate, suggesting that energycane exhibited tolerance to POST application of these herbicides. Ametryn and metribuzin did not cause injury at the 1× rate. The highest application rate of metribuzin caused 8 to 10% injury to energycane. Significant injury was observed for the highest rate (2×) of ametryn (8%). Atrazine, carfentrazone, 2,4-D amine, dicamba, halosulfuron, mesotrione, and metribuzin are labeled for use in sugarcane (Shaner 2014), which may explain why they did not cause injury to energycane at the 1× rate. Similar to sugarcane, energycane may be susceptible to injury from asulam and trifloxysulfuron if used for POST grass control.

There was a negative correlation of herbicide injury with aboveground ($r = -0.87$, $P < 0.01$) and belowground ($r = -0.86$, $P < 0.01$) biomass of energycane for the first experimental run. Herbicide injury was also negatively correlated with aboveground ($r = -0.77$, $P < 0.01$) and belowground ($r = -0.72$, $P < 0.01$) biomass of energycane for the second experimental run. Similar to injury, treatments containing 2,4-D amine, ametryn, asulam, atrazine, carfentrazone, dicamba, halosulfuron, and mesotrione were not significantly different from the nontreated control with regard to aboveground and belowground biomass of energycane regardless of application rate (Tables 3 and 4). This demonstrated that energycane was highly tolerant to these POST herbicides. These herbicides can potentially be used alone or in combination to broaden the spectrum of weed control in energycane. Metribuzin was not significantly different from the nontreated control, with the exception of aboveground and belowground biomass at the highest application rate (2×). Injury by trifloxysulfuron was not significantly different from the nontreated control with the exception of belowground biomass at the highest application rate (2×) for the first experimental run. Although trifloxysulfuron caused significant injury compared with the nontreated control for the second experimental run, both aboveground and belowground biomass were not significantly different from the nontreated control. Other herbicides, including clethodim, clomazone, diuron, flumioxazin, glufosinate, glyphosate, hexazinone, paraquat, and sethoxydim, which caused severe injury to energycane, also significantly reduced both aboveground and belowground biomass compared with the nontreated control, except at the lowest rate (1×) of clomazone.

Based on our results, several PRE herbicides, including atrazine, diuron, mesotrione, metribuzin, pendimethalin, and *S*-metolachlor, at labeled rates for sugarcane can potentially be applied for weed control in newly established energycane on marginal mineral soils in Florida. Similarly, 2,4-D amine, ametryn, asulam, atrazine, carfentrazone, dicamba, halosulfuron, mesotrione, and metribuzin can be used for POST weed control in newly established energycane at labeled rates for sugarcane. Although combinations of these herbicides can potentially increase the efficacy and broaden the spectrum of weed control in energycane, further studies are needed to evaluate their safety on the crop. Also, even though energycane exhibited tolerance to metribuzin, it cannot be used on mineral soils in Florida because of concerns regarding groundwater contamination. Metribuzin can only be used in Florida on soils high in organic matter and clay content because of concerns of groundwater contamination. The results of the study also showed that graminicides (clethodim, sethoxydim) and glyphosate would be effective in controlling newly established energycane escapes in vegetables and fallow sugarcane fields, respectively. In addition, the graminicides and glyphosate could potentially be used for spot

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treatment of energycane escapes in sugarcane. However, control of energycane in sugarcane with currently available sugarcane grass herbicides, asulam and trifloxysulfuron, would be difficult if energycane escaped and became established in the crop.

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