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Switchgrass and Prairie Cordgrass Response to Foliar- and Soil-Applied Herbicides

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Perennial grasses are expected to comprise a substantial portion of the lignocellulosic biomass to meet renewable energy mandates in the U.S. in the next decade. As many warm-season grasses are slow to establish from seed, plantings are often compromised by weed interference during the establishment year. Greenhouse experiments were conducted to determine the tolerance of switchgrass and prairie cordgrass to several herbicides applied PRE or POST (at four different growth stages). Preemergence atrazine at rates $\leq$ 1.684 kg ai ha^{-1} in switchgrass and quinclorac at rates $\leq$ 0.279 kg ai ha^{-1} in prairie cordgrass did not significantly reduce emergence, plant height, or biomass yield 8 wk after treatment. When treatments were applied at the two- to three-leaf stage, only atrazine ($\leq$ 0.123 kg ai ha^{-1}) did not reduce switchgrass fresh weight and only 2,4-D ester ($\leq$ 0.533 kg ae ha^{-1}), nicosulfuron (0.018 kg ai ha^{-1}), and quinclorac (0.140 kg ha^{-1}) did not significantly reduce prairie cordgrass yield. Phytotoxic effects decreased for all herbicides with increasing growth stage at the time of treatment for both species. All evaluated herbicides were safe with respect to biomass yield on the respective grasses when applied at the latest growth stage (approximately five-leaf stage). These results show that viable PRE and POST herbicides are available for weed control during establishment of switchgrass and prairie cordgrass; however, all evaluated herbicides would likely reduce biomass yield in a mixture planting of both grasses.
Nomenclature: 2,4-D ester; atrazine; nicosulfuron; quinclorac; prairie cordgrass, *Spartina pectinata* Link; switchgrass, *Panicum virgatum* L.
Key words: Bioenergy feedstock, establishment, herbicide injury, herbicide tolerance, lignocellulosic biomass.

Se espera que las gramíneas perennes representen una porción sustancial de la biomasa lignocelulósica para cumplir con los mandatos de energías renovables en los Estados Unidos en la próxima década. Debido a que muchos de las gramíneas de clima cálido tienen un establecimiento lento a partir de semilla, las plantaciones están frecuentemente en riesgo debido a la interferencia de malezas durante el año de establecimiento. Se realizaron experimentos de invernadero para determinar la tolerancia de *Panicum virgatum* y de *Spartina pectinata* a varios herbicidas aplicados PRE o POST (en cuatro estadios de crecimiento diferentes). Atrazine en preemergencia a dosis $\leq$ 1.684 kg ai ha^{-1} en *P. virgatum* y quinclorac a dosis $\leq$ 0.279 kg ai ha^{-1} en *S. pectinata* no redujeron significativamente la emergencia, la altura de planta, ni el rendimiento de biomasa 8 semanas después del tratamiento. Cuando los tratamientos fueron aplicados en los estadios de dos a tres hojas, solamente atrazine ($\leq$ 0.123 kg ai ha^{-1}) no redujo el peso seco de *P. virgatum* y solamente 2,4-D ester ($\leq$ 0.533 kg ae ha^{-1}), nicosulfuron (0.018 kg ai ha^{-1}), y quinclorac (0.140 kg ai ha^{-1}) no redujeron significativamente el rendimiento de *S. pectinata*. Los efectos fitotóxicos disminuyeron para todos los herbicidas con el aumento en el estadio de crecimiento al momento del tratamiento para ambas especies. Todos los herbicidas evaluados fueron seguros con respecto al rendimiento de biomasa en las respectivas gramíneas cuando se aplicó en el estadio de crecimiento más tardío (aproximadamente estadio de 5-hojas). Estos resultados muestran que herbicidas PRE y POST viables están disponibles para el control de malezas durante el establecimiento de *P. virgatum* y *S. pectinata*. Sin embargo, todos los herbicidas evaluados probablemente reducirán el rendimiento de biomasa en una siembra mixta con ambas gramíneas.

Production of lignocellulosic biomass feedstocks in the U.S. is expected to increase as the demands for advanced biofuels and low-carbon electricity generating fuel sources increase. The most recent version of the Renewable Fuel Standard (RFS2) (Schnepf and Yacobucci 2013) requires that 60.5

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billion L of ethanol-equivalent cellulosic biofuels be blended into transportation fuels by 2022 as mandated by the Energy Independence and Security Act of 2007 (EISA 2007). To meet this mandate, over 195 million Mg of biomass will need to be produced annually, assuming a conversion factor of 310 L per Mg of biomass in a sugars-to-ethanol biochemical conversion process (Somerville et al. 2010). Although agricultural and forestry residues constitute the majority of biomass currently available, purpose-grown biomass crops such as perennial grasses and woody species are expected to be the largest single source by 2022 (USDA 2011).

Switchgrass is a perennial, warm-season, C4 grass native to the U.S. (Hitchcock 1971). The U.S. Department of Energy has identified switchgrass as a model energy crop due to its high biomass yields and its adaptability to a wide range of soil types and climatic conditions (Lynd et al. 1991; Sanderson et al. 1996). Switchgrass populations occur as lowland (typically originating geographically <40°N, higher yielding with less drought tolerance) or upland (usually originating geographically > 40°N, generally lower yielding with greater drought tolerance) ecotypes (Parrish and Fike 2009; Parrish et al. 2008). Economic viability of switchgrass grown for bioenergy is dependent on successful stand establishment (Perrin et al. 2008), and weed control is typically a critical factor (Boydston et al. 2010; Martin et al. 1982; Miesel et al. 2012; Mitchell et al. 2010; Parrish et al. 2008; Vogel 1987).

Several studies have been completed to identify effective herbicide options in switchgrass. Switchgrass was tolerant of atrazine applied PRE on clay loam or silty clay loam soils at 2.2 and 3.0 kg ai ha^{-1} (Vogel 1987) and as high as 3.4 kg ha^{-1} (Martin et al. 1982). A PRE tank mixture of atrazine + quinclorac (1.1 and 0.56 kg ai ha^{-1}, respectively) provided good weed control (<(10% weed contribution to biomass) and was safe on several upland and lowland switchgrass cultivars (Mitchell et al. 2010). Hintz et al. (1998) found that a single PRE application of atrazine (2.8 kg ha^{-1}) provided sufficient weed control and successful switchgrass establishment. McKenna et al. (1991) found that atrazine applied at 1.1 or 2.2 kg ha^{-1} reduced switchgrass growth the year of establishment, but only the higher rate reduced yields the year after planting in only one of four experiments. A POST application of 2,4-D amine + dicamba (each at 0.28 kg ae ha^{-1}) with or without atrazine (1.1 kg ha^{-1}) + quinclorac (0.42 kg ha^{-1}) was safe on switchgrass when applied about 6 wk after seeding, although the application including atrazine and quinclorac provided better weed control and generally higher switchgrass yields (Curran et al. 2012).

Although atrazine can be used for effective weed control in switchgrass, its application is restricted in several regions and soil types in the U.S. Therefore, it is imperative that other herbicide options are available for a wide range of soils, climates, weed types (particularly grass weeds) and management situations. Pendimethalin applied PRE or POST at 0.74 to 1.1 kg ai ha^{-1} provided excellent weed control but severely impacted the establishing switchgrass stands on sandy soils (Fransen et al. 2006). Pendimethalin applied PRE or at the one-leaf stage (at 0.67 and 1.0 kg ha^{-1}, respectively) significantly injured and reduced stands of upland and lowland switchgrass (Boydston et al. 2010). Minelli et al. (2004) also found that pendimethalin applied PRE (1.23 kg ha^{-1}) reduced switchgrass emergence by > 50%. Mesotrione (0.07 kg ha^{-1}) significantly injured and reduced switchgrass yield, especially upland cultivars, while quinclorac (0.56 kg ha^{-1}) was safe when applied at the four- to six-leaf stage (Boydston et al. 2010). Quinclorac is labeled for use on switchgrass grown for seed when applied at 0.28 kg ha^{-1} (Anonymous 2008b).

Various herbicides that inhibit acetolactate synthase (ALS) have been evaluated for potential use in switchgrass. McKenna et al. (1991) found that two reduced POST applications of nicosulfuron (0.020 kg ai ha^{-1}) plus dicamba (0.028 kg ha^{-1}) plus MCPA (0.318 kg ai ha^{-1}) provided the best weed control and the highest switchgrass biomass yields. Nicosulfuron can be applied to switchgrass grown as a biofuel feedstock in Tennessee at the two-leaf stage or later at 0.035 kg ha^{-1} (Anonymous 2008a). Imazapyr and imazethapyr applied PRE and imazethapyr applied POST (each at 0.045, 0.070, or 0.110 kg ai ha^{-1}) produced varied results at different sites but generally improved switchgrass establishment compared with a non-treated control (Masters et al. 1996). Imazethapyr (0.07 or 0.14 kg ha^{-1}) applied at the three- to five-leaf stage of switchgrass stunted plant height, but also increased plant density and biomass yield compared with a non-treated control (Wilson 1995). Imazapic

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(0.035 kg ai ha^{-1}) significantly reduced switchgrass stands at two of three locations in the upper Great Plains and was not recommended for weed control during switchgrass establishment (Mitchell et al. 2010).

Prairie cordgrass is a perennial, rhizomatous, C4 grass that is native to most of the U.S. and Canada to 60°N latitude (Weaver 1954). Prairie cordgrass has produced comparable yields (Madakadze et al. 1998) and outperformed switchgrass in biomass production on well-drained (Boe and Lee 2007) and marginal soils (Boe et al. 2009). Prairie cordgrass grows taller and more rapidly than other prairie grasses and has an aggressive rhizome system, allowing it to form dense pure stands (Boe et al. 2009; Weaver 1954). Therefore, weed control is generally not necessary in mature stands. During the establishment year, prairie cordgrass seed germinates throughout the summer and seedling vigor is only moderate (Jensen 2013), so season-long weed control is critical. Few studies have been reported that describe herbicide phytotoxicity on prairie cordgrass. Sekutowski and Dziagwa (2012) found that foramsulfuron + iodosulfuron (0.045 + 0.002 kg ai ha^{-1}) effectively controlled grass (e.g., *Apera spica-venti* (L.) P. Beauv. and *Echinochloa crus-galli* (L.) P. Beauv.) and broadleaf (e.g., *Thlaspi arvense* L. and *Stellaria media* (L.) Vill.) weeds, but significantly injured prairie cordgrass in a field study near Wroclaw, Poland. Both iodosulfuron + propoxycarbazone + amidosulfuron (0.002 + 0.042 + 0.018 kg ai ha^{-1}) and especially sulcotrione (0.45 kg ai ha^{-1}) produced initial injury symptoms (primarily leaf chlorosis) that subsided within 4 wk of treatment; however, neither provided satisfactory weed control. If prairie cordgrass is to be planted at agronomic scale as a biomass feedstock in the United States, research will be needed to identify herbicide options and other methods of weed control.

Herbicide options for switchgrass are fairly well known, and several herbicides are currently labeled for use in switchgrass, generally at the three- to four-leaf stage onward. However, much less is known about herbicide options for use in prairie cordgrass establishment. An ideal weed control system would include both foliar- and soil-applied herbicides with activity on a broad range of grass and broadleaf weeds that would be safe to use in both species since mixture plantings are often desirable to maximize yield and minimize year-to-year biomass production variability (Hong et al. 2013; Tilman 1996; Tilman et al. 1996). The objectives of the current experiments were to determine switchgrass and prairie cordgrass tolerance of various PRE herbicides applied at two different rates and POST herbicides applied at two different rates applied at several plant growth stages under greenhouse conditions.

Materials and Methods

Response to PRE Herbicides. A greenhouse experiment was designed as a randomized complete block with four replications in space and three replications in time. A mix of soil, peat and torpedo sand medium (1 : 1 : 1 by wt) was prepared with the addition of dolomitic lime, phosphate (0-46-0), gypsum, and $MgSO_4$ (2.7, 1.1, 1.6, and 1.1 kg m^{-3}, respectively). Seeds were planted at a depth of 3 mm with 20 switchgrass (EG 2101, an improved 'Cave-in-Rock' upland cultivar, Blade® Energy Crops, Thousand Oaks, CA, 91320) or prairie cordgrass (pc46-109, a wild accession from South Dakota) seeds per 12.7 by 12.7 by 5.7 cm cell. Herbicides evaluated and their respective 1× rates are presented in Table 1. Application rates were 1/2× and 1× of recommended labeled rates for corn (*Zea mays* L.), when applicable, grown in silt loam or silty clay loam with 2 to 3% soil organic matter. Treatments were applied the day of planting using a compressed air spray chamber (Allen Machine Works, 607 E. Miller Rd., Midland, MI 48640) calibrated to deliver 187 L ha^{-1} at 207 kPa through a traveling nozzle (XR80015) (TeeJet Technologies, P.O. Box 7900, Wheaton, IL 60189) 45 cm above the soil surface. Cells were irrigated with 2 cm of water immediately after treatment to incorporate the active ingredients, then at least daily for the duration of the experiment. All watering was done from above with a flow-breaker nozzle at a maximum of 1 cm per pass to minimize soil surface disturbance and leaching.

Temperature was maintained between 16 and 30 C during the night and day, respectively, throughout the experiment. High-intensity-discharge high pressure sodium lamps (STIM-U-Lyte GR-HPS-1000W, Voigt Lighting, 79 Commerce St., Garfield, NJ 07026) provided supplementary lighting (450 μmol m^{-2} s^{-1} photon flux at plant canopy

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Table 1. Herbicide treatments applied to switchgrass and/or prairie cordgrass.

Common name	1× Rate kg ai (ae) ha^{-1}	Application timing	Trade name	Manufacturer	City, state
2,4-D ester[a]	0.533 (ae)	POST	Weedone LV4	Nufarm	Burr Ridge, IL
Acetochlor	1.670	POST	Harness	Monsanto Company	St. Louis, MO
Acetochlor + atrazine	1.670 + 1.123	POST	Harness Xtra	Monsanto Company	St. Louis, MO
Atrazine	1.684	PRE	AAtrex	Syngenta Crop Protection	Greensboro, NC
Atrazine	1.123	POST	AAtrex	Syngenta Crop Protection	Greensboro, NC
Imazapic	0.070 (ae)	PRE	Plateau	BASF	Research Triangle Park, NC
Imazethapyr	0.070 (ae)	PRE	Pursuit	BASF	Research Triangle Park, NC
Mesotrione	0.105	PRE	Callisto	Syngenta Crop Protection	Greensboro, NC
Mesotrione + atrazine	0.105 + 1.684	PRE	Callisto Xtra	Syngenta Crop Protection	Greensboro, NC
Nicosulfuron[b]	0.035	POST	Accent	E. I. du Pont de Nemours and Company	Wilmington, DE
Pendimethalin	1.600	PRE	Prowl H_2O	BASF	Research Triangle Park, NC
Prodiamine	0.737	PRE, POST	Barricade	Syngenta Crop Protection	Greensboro, NC
Quinclorac[c]	0.279	PRE, POST	Paramount	BASF	Research Triangle Park, NC
S-metolachlor + mesotrione + atrazine	2.257 + 0.226 + 0.842	POST	Lumax	Syngenta Crop Protection	Greensboro, NC
Simazine	2.245	PRE	Princep	Syngenta Crop Protection	Greensboro, NC
Sulfentrazone + chlorimuron ethyl	0.209 + 0.026	PRE	Authority XL	FMC	Philadelphia, PA
Sulfosulfuron[a,d]	0.074	PRE, POST	Certainty	Monsanto Company	St. Louis, MO
Thiencarbazone-methyl + isoxaflutole[a]	0.037 + 0.092	POST	Corvus	Bayer CropScience	Research Triangle Park, NC

[a] Includes ammonium sulfate @ 2.5% v/v when applied POST.

[b] Includes crop oil concentrate @ 1% v/v.

[c] Includes methylated seed oil @ 1% v/v when applied POST.

[d] ncludes nonionic surfactant @ 0.25% v/v when applied POST.

Table 2. Growth stage plant characteristics and environmental conditions at the time of POST herbicide applications for switchgrass and prairie cordgrass.

Growth stage	Plant height[a,b]	Leaf number	Herbicide application timing	GDD[c]	PAR[d]
	cm				μmol m^{-2} s^{-1}
Switchgrass					
Early-POST	8	2–3	3	477	446,000
Mid1-POST	19	2–4	3	655	900,000
Mid2-POST	30	3–4	6	893	1,129,000
Late-POST	59	4–5	6	1,275	2,217,000
Prairie cordgrass					
Early-POST	14	2–3	3	477	446,000
Mid1-POST	33	3–5	3	655	900,000
Mid2-POST	40	3–5	6	893	1,129,000
Late-POST	66	5–6	6	1,275	2,217,000

[a] Average height of all plants across replications.

[b] Herbicide application timing measured in weeks after planting.

[c] Growing degree days, base 10 C.

[d] Accumulated photosynthetically active radiation from planting to herbicide application, measurements taken every 15 min.

level) when necessary for up to 14 h d^{-1}. Plant emergence, height of the tallest shoot, and visual assessment of herbicide injury were recorded at 1, 2, 4, and 8 wk after treatment (WAT). Herbicide injury was rated on a scale from 0 (no green tissue) to 100 (only green tissue) to allow for more understandable presentation of data as percentages of non-treated controls. Following the final evaluation, plants were cut at the soil level and weighed, and select samples were then dried at 60 C for at least 48 h to determine correlation between fresh and dry weights. Only data from 8 WAT are presented.

Response to POST Herbicides. A greenhouse experiment was conducted as a factorial within a randomized complete block design with four replications in space and two replications in time. Switchgrass and prairie cordgrass seeds were planted according to the protocol for the PRE herbicides experiment. Herbicides evaluated and their respective 1× rates are listed in Table 1. Herbicides were applied at 1/2× and 1× rates at four different growth stages (early-POST, mid1-POST, mid2-POST and late-POST) as described in Table 2. Herbicide application and irrigation followed the protocol for the PRE herbicides experiment except that watering was withheld for 24 h following treatment to allow for foliar absorption of herbicides. Cells were then watered at least daily for the remainder of the experiment. Temperatures were maintained between 30 C during the day and 16 C at night throughout the experiment. Height of the tallest shoot, herbicide injury ratings and tissue weight were measured according to the procedure for the PRE herbicides experiment at 1, 2, 4, and 8 WAT. Only final measurements at 8 WAT are presented.

Statistical Analysis. Data for each species and experiment (PRE and POST) were analyzed separately. For the PRE experiment, herbicide treatment was considered a fixed effect while replication and block were considered random effects. For the POST experiment, herbicide treatment, plant growth stage and their interaction were considered fixed effects while replication and block were considered random effects. Normality of the residuals was evaluated using box plots in the UNIVARIATE procedure and equality of the variances was evaluated using plots of the observed versus predicted residuals in SAS (SAS Institute, 2008. The SAS System for Windows, Version 9.2. SAS Institute, Inc., Cary, NC). All data were analyzed at $\alpha = 0.05$ using the MIXED procedure in SAS. Pair-wise differences from the MIXED procedure were used to create letter groupings of similar means using the PDMIX800 macro in SAS (Saxton 1998). Pearson product–moment correlation was used to identify significant correlations among all quantitative dependent variables and Spearman rank-order correlation was used to identify

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correlations with injury rating using the CORR procedure in SAS.

Results and Discussion

Response to PRE Herbicides. Herbicide treatment was significant ($P < 0.0001$) for all dependent variables tested in switchgrass and prairie cordgrass. Biomass fresh weight was highly correlated with dry weight for switchgrass and prairie cordgrass (0.98, $P < 0.0001$ and 0.81, $P < 0.0001$, respectively), and only fresh weights are presented. Previous work with perennial grasses has also shown a very high correlation between fresh and dry aboveground biomass weights (Anderson et al. 2014; Anderson et al. 2011). Plant emergence in switchgrass was not statistically different from the non-treated control with atrazine, simazine, imazapic and imazethapyr at both rates tested (Table 3). Emergence was not significantly reduced at the 1/2× rate with mesotrione, pendimethalin, quinclorac and sulfentrazone + chlorimuron ethyl compared with the control. Only sulfosulfuron at both rates and sulfentrazone + chlorimuron ethyl at the 1× rate caused significant injury to switchgrass at 8 WAT. Injury symptoms included chlorosis and bleaching (stunting was not considered in the ratings since plant height was measured separately). Plants generally outgrew bleaching symptoms within 4 WAT. Injury ratings were only weakly correlated with any other parameter (e.g., correlation of injury to fresh weight was −0.48, $P < 0.0001$). Atrazine, imazethapyr, pendimethalin, and quinclorac did not significantly reduce plant height compared with the non-treated control at both rates. However, only atrazine at both rates tested and imazethapyr and quinclorac at the 1/2× rate did not significantly reduce aboveground biomass fresh weight compared with the non-treated control.

Results showed that atrazine applied PRE was safe on switchgrass at both rates tested which confirms several previous studies (Curran et al. 2012; Martin et al. 1982; Mitchell et al. 2010; Vogel 1987). However, all other herbicides significantly impacted all measured plant growth components at the rates tested. Several herbicides proved to be marginally safe and may be considered in certain weed management situations, including imazapic, imazethapyr, pendimethalin, quinclorac and simazine. However, field testing is needed to determine plant response and herbicide impact on biomass yield as previous studies have shown pendimethalin (Boydston et al. 2010; Fransen et al. 2006; Minelli et al. 2004), imazethapyr (Masters et al. 1996) and imazapic (Mitchell et al. 2010) produced negative or mixed phytotoxic responses.

Emergence in prairie cordgrass was not statistically different from the non-treated control with sulfosulfuron, quinclorac, pendimethalin, imazapic or sulfentrazone + chlorimuron ethyl at the rates tested (Table 3). Although atrazine at the 1/2× rate did not significantly reduce emergence, treatment with the 1× rate reduced prairie cordgrass emergence by 76%. Injury was not correlated with any other measured parameter (e.g., correlation between injury and fresh weight was −0.03, $P = 0.67$). Atrazine, mesotrione + atrazine, pendimethalin, quinclorac, simazine, and sulfentrazone + chlorimuron ethyl did not cause significant injury at both rates tested. Imazethapyr and sulfosulfuron produced an acceptable level of injury (i.e., less than 25% non-green tissue) at both rates tested, although injury was statistically different from the non-treated control at the 1× rate. Percent green tissue with imazapic at the 1/2× rate was lower than at the 1× rate due to unusually low ratings in one replication. Pendimethalin, mesotrione, quinclorac, sulfosulfuron and sulfentrazone + chlorimuron ethyl did not significantly reduce plant height compared with the non-treated control at both rates. However, similar to biomass yield with switchgrass, most herbicides significantly reduced fresh weight except quinclorac at both rates, and mesotrione, sulfosulfuron and pendimethalin at the 1/2× rate.

These results show that quinclorac, sulfosulfuron, pendimethalin and possibly mesotrione are good candidates for preemergence weed control in prairie cordgrass seeding, although biomass yield at 8 WAT declined 10–30% with these herbicides at the 1× rate under greenhouse conditions. Field experiments are needed to determine weed-control efficacy and impact on prairie cordgrass growth.

Unfortunately, none of the tested PRE herbicides were safe on both switchgrass and prairie cordgrass under greenhouse conditions. Weed control in plantings that include both of these grasses will likely be difficult during the establishment year. Quinclorac and pendimethalin, along with atrazine at lower application rates, appear to be the best

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Table 3. Emergence, herbicide injury, plant height and fresh weight of switchgrass and prairie cordgrass as percentages of the non-treated controls following PRE treatments at two herbicide rates.

Herbicide treatment	Rate kg ai (ae) ha^{-1}	Emergence[a,b]		Green tissue		Plant height		Fresh weight	
Switchgrass									
Non-treated control	—	100 (64)	AB	100	A	100 (59)	A	100 (6.84)	A
Atrazine	0.842	103	AB	100	A	82	ABCD	103	A
	1.684	106	A	100	A	96	A	97	AB
Imazapic	0.035	90	ABCD	97	A	62	CDEF	38	GHIJ
	0.070 (ae)	79	ABCDE	94	A	70	BCDE	52	DEFGH
Imazethapyr	0.035	92	ABC	100	A	90	AB	84	ABC
	0.070 (ae)	81	ABCDE	94	A	75	ABCDE	40	FGHIJ
Mesotrione	0.053	90	ABCD	89	AB	82	ABCD	72	BCDE
	0.105	54	EFGH	87	ABC	54	EFG	32	HIJK
Mesotrione + atrazine	0.053 + 0.842	53	EFGH	90	AB	63	CDEF	48	EFGHI
	0.105 + 1.684	43	GH	98	A	37	FGH	23	IJK
Pendimethalin	0.800	81	ABCDE	100	A	84	ABCD	67	CDEF
	1.600	67	CDEFG	100	A	81	ABCD	53	DEFGH
Prodiamine	0.369	32	HI	100	A	52	EFGH	21	IJK
	0.737	9	I	100	A	29	GHI	8	K
Quinclorac	0.140	77	BCDE	97	A	86	ABCD	76	ABCD
	0.279	71	CDEF	100	A	87	ABC	61	CDEFG
Simazine	1.123	101	AB	100	A	61	CDEF	54	DEFGH
	2.245	91	ABC	100	A	60	DEF	37	GHIJ
Sulfentrazone + chlorimuron ethyl	0.105 + 0.013	80	ABCDE	89	AB	27	HI	15	JK
	0.209 + 0.026	45	FGH	78	BC	8	I	5	K
Sulfosulfuron	0.037	71	CDEFG	75	C	30	GHI	18	JK
	0.074	63	DEFG	56	D	9	I	7	K
Prairie cordgrass									
Non-treated control	—	100 (55)	A	100	A	100 (66)	ABCD	100 (5.30)	A
Atrazine	0.842	81	ABC	100	A	82	BCDEFG	50	DEFG
	1.684	24	H	92	ABC	47	IJ	14	IJ
Imazapic	0.035	83	ABC	72	DE	63	FGHI	44	EFGH
	0.070 (ae)	77	ABCD	89	ABC	46	IJ	29	GHI
Imazethapyr	0.035	74	BCDE	83	BCD	86	ABCDEF	60	CDEF
	0.070 (ae)	79	ABC	78	CD	54	HIJ	31	GHI
Mesotrione	0.053	87	ABC	94	ABC	105	AB	86	AB
	0.105	65	CDE	83	BCD	95	ABCDE	64	BCDE
Mesotrione + atrazine	0.053 + 0.842	49	EFG	97	AB	76	CDEFGH	25	HIJ
	0.105 + 1.684	24	GH	95	ABC	19	K	3	J
Pendimethalin	0.800	90	ABC	100	A	109	A	82	ABC
	1.600	83	ABC	97	AB	102	ABC	73	BCD
Prodiamine	0.369	52	DEF	94	ABC	75	DEFGH	28	GHI
	0.737	38	FGH	61	E	34	JK	13	IJ
Quinclorac	0.140	90	ABC	86	ABCD	101	ABC	96	A
	0.279	86	ABC	86	ABCD	92	ABCDE	80	ABC
Simazine	1.123	67	CDE	97	AB	70	EFGHI	45	EFGH
	2.245	81	ABC	100	A	57	GHIJ	22	HIJ
Sulfentrazone + chlorimuron ethyl	0.105 + 0.013	96	AB	97	AB	87	ABCDEF	56	DEF
	0.209 + 0.026	76	ABCD	92	ABC	84	ABCDEF	41	FGH
Sulfosulfuron	0.037	100	A	92	ABC	91	ABCDE	84	AB
	0.074	93	AB	83	BCD	78	CDEFGH	70	BCD

[a] Letters denote groupings within columns for each species, $\alpha = 0.05$.

[b] Values in parentheses are the means for percent emergence, plant height (cm) and fresh weight (g).

[c] Herbicide injury was evaluated as the percent of green leaf and stem tissue for continuity of comparison.

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options in a mixed planting, but higher seeding rates may be necessary to ensure adequate stand establishment.

Response to POST Herbicides. Herbicide treatment, plant growth stage and the interaction term were highly significant ($P < 0.0001$) for all dependent variables in switchgrass and prairie cordgrass. The trend for all parameters in both species was increasing means compared with non-treated controls with increasing plant growth stage at the time of herbicide treatment. There were, however, several instances where measured parameters did not follow this pattern. Since there was no consistent pattern across variables for any herbicide treatment other than the one previously described, it is assumed that deviations from that trend were due to variability within each cultivar (switchgrass) or germplasm (prairie cordgrass), greenhouse bench conditions, herbicide application uniformity, or some combination of these conditions.

Switchgrass treated with atrazine or prodiamine exhibited very little or no injury symptoms at both rates tested and all growth stages (Table 4). All other herbicide treatments resulted in significant injury at both rates through the mid2-POST stage except for acetochlor at 1/2× at the mid2-POST stage. However, all herbicide treatments were safe on switchgrass at the late-POST stage. S-metolachlor + mesotrione + atrazine at the 1/2× rate was statistically different from the non-treated control, but injury ratings greater than 75 were considered acceptable. Injury was moderately correlated with plant height in switchgrass (–0.61, $P < 0.0001$). Switchgrass height was also not significantly affected by atrazine or prodiamine at any growth stage. As with injury, the impact of all herbicide treatments on height decreased with increasing growth stage, and all herbicide treatments were safe on switchgrass with respect to height when applied at the late-POST stage.

Fresh weight was highly correlated with dry weight in switchgrass and prairie cordgrass (0.95, $P < 0.0001$ and 0.97, $P < 0.0001$, respectively), and only fresh weight data are presented. Fresh weight was highly correlated with height (0.86, $P < 0.0001$) and moderately correlated with injury (–0.71, $P < 0.0001$) in switchgrass. Atrazine and prodiamine did not significantly reduce switchgrass fresh weight at any rate or growth stage compared with the non-treated control (Table 4). The same general trend with increasing means with increasing plant growth stage at the time of herbicide treatment was observed with fresh weight. Certain herbicide treatments, including acetochlor with and without atrazine, were also generally safe with respect to fresh weight at the mid1-POST and mid2-POST stages. No fresh weights were significantly lower than the non-treated control when herbicides were applied at the late-POST stage.

Prairie cordgrass treated with quinclorac or 2,4-D ester at both rates and nicosulfuron at the 1/2× rate at the early-POST stage exhibited little or no injury (Table 5). At mid1-POST, only atrazine and acetochlor + atrazine at the 1× rate produced unacceptable levels of injury. At mid2-POST, only herbicide treatments containing acetochlor produced unacceptable levels of injury, and all herbicide treatments were safe on prairie cordgrass with respect to injury when applied at the late-POST stage.

Injury was only weakly correlated with prairie cordgrass plant height (–0.57, $P < 0.0001$). Plant height was not significantly reduced compared with the non-treated control with quinclorac or 2,4-D ester at both rates and with nicosulfuron and prodiamine at the 1/2× rate when applied at the early-POST stage (Table 5). Only herbicide treatments containing acetochlor significantly reduced plant height when applied at mid2-POST. Acetochlor also significantly reduced plant height compared with the non-treated control when applied at late-POST (except acetochlor at the 1/2× rate), although they were not significantly different at the mid1-POST stage due to the comparison with the relatively tall plants treated with quinclorac.

Fresh weight was highly correlated with height (0.82, $P < 0.0001$) and moderately correlated with injury (–0.63, $P < 0.0001$) in prairie cordgrass. Only 2,4-D ester at both rates and quinclorac and nicosulfuron at the 1/2× rate did not reduce biomass yield significantly at the early-POST stage (Table 5). Fresh weight response was varied when herbicides were applied at mid1- and mid2-POST stages. Fresh weight was not reduced by 2,4-D ester except for the uncharacteristically low yield at the 1/2× rate at mid1-POST; fresh weights for one replication in time were consistently low compared with the 1× rate suggesting an application error. Nicosulfuron was safe at both rates at mid2-POST

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Table 4. Herbicide injury, plant height and fresh weight of switchgrass as percentages of the non-treated controls following POST treatments at two herbicide rates and four growth stages.

Herbicide treatment	Rate	Growth stage[a]							
	kg ai ha^{-1}	Early-POST		Mid1-POST		Mid2-POST		Late-POST	
Injury[b,c]									
Non-treated control	—	100	A	100	A	100	A	100	A
Acetochlor	0.835	69	B	100	A	81	AB	92	A
	1.67	48	C	100	A	73	BC	92	A
Acetochlor + atrazine	0.835 + 0.562	48	C	100	A	71	BC	88	A
	1.670 + 1.123	2	E	100	A	71	BC	100	A
Atrazine	0.562	100	A	100	A	96	A	100	A
	1.123	100	A	100	A	100	A	100	A
Prodiamine	0.369	100	A	100	A	96	A	100	A
	0.737	96	A	100	A	100	A	100	A
S-metolachlor + mesotrione + atrazine	1.129 + 0.113 + 0.421	0	E	67	B	67	BC	81	B
	2.257 + 0.226 + 0.842	0	E	31	C	60	C	94	A
Sulfosulfuron[d,e]	0.037	42	CD	63	B	54	C	92	A
	0.074	25	D	71	B	52	C	96	A
Thiencarbazone-methyl + isoxaflutole[d]	0.019 + 0.046	50	BC	69	B	75	BC	96	A
	0.037 + 0.092	17	DE	33	C	54	C	100	A
Plant height[f]									
Non-treated control	—	100 (67)	A	100 (92)	A	100 (63)	A	100 (99)	A
Acetochlor	0.835	51	B	94	AB	88	A	87	A
	1.67	27	C	103	A	86	AB	103	A
Acetochlor + atrazine	0.835 + 0.562	26	C	92	AB	87	A	96	A
	1.670 + 1.123	3	D	86	AB	72	AB	96	A
Atrazine	0.562	90	A	107	A	92	A	100	A
	1.123	108	A	109	A	94	A	106	A
Prodiamine	0.369	101	A	102	A	91	A	101	A
	0.737	90	A	86	AB	90	A	93	A
S-metolachlor + mesotrione + atrazine	1.129 + 0.113 + 0.421	0	D	107	A	72	AB	92	A
	2.257 + 0.226 + 0.842	0	D	73	B	56	B	106	A
Sulfosulfuron[d,e]	0.037	30	BC	88	AB	63	B	96	A
	0.074	16	CD	78	B	59	B	97	A
Thiencarbazone-methyl + isoxaflutole[d]	0.019 + 0.046	42	BC	73	B	74	AB	96	A
	0.037 + 0.092	14	CD	33	C	60	B	86	A
Fresh weight[f]									
Non-treated control	—	100 (16.52)	AB	100 (15.63)	B	100 (11.71)	AB	100 (21.40)	AB
Acetochlor	0.835	15	C	92	B	87	B	88	B
	1.67	7	C	95	B	62	BC	111	AB
Acetochlor + atrazine	0.835 + 0.562	3	C	90	B	66	BC	92	B
	1.670 + 1.123	0	C	82	B	60	C	96	B

Table 4. Continued.

Herbicide treatment	Rate	Growth stage[a]							
	kg ai ha^{-1}	Early-POST		Mid1-POST		Mid2-POST		Late-POST	
Atrazine	0.562	87	AB	113	AB	118	A	104	AB
	1.123	104	A	129	A	118	A	91	B
Prodiamine	0.369	78	B	123	A	120	A	110	AB
	0.737	65	B	115	AB	109	AB	106	AB
S-metolachlor + mesotrione + atrazine	1.129 + 0.113 + 0.421	0	C	90	B	61	C	94	B
	2.257 + 0.226 + 0.842	0	C	19	D	56	C	124	A
Sulfosulfuron[d,e]	0.037	9	C	74	BC	49	C	101	AB
	0.074	5	C	50	C	57	C	117	AB
Thiencarbazone-methyl + isoxaflutole[d]	0.019 + 0.046	12	C	47	C	79	BC	95	B
	0.037 + 0.092	2	C	12	D	46	C	85	B

[a] Growth stage of the plants at the time of treatment as outlined in Table 2.
[b] Herbicide injury was evaluated as the percent of green leaf and stem tissue for continuity of comparison.
[c] Letters denote groupings within columns for each growth stage, $\alpha = 0.05$.
[d] Includes ammonium sulfate @ 2.5% v/v.
[e] Includes nonionic surfactant @ 0.25% v/v.
[f] Values in parentheses are the means for plant height (cm) and fresh weight (g).

but at neither rate at mid1-POST, while response to quinclorac was the opposite. Atrazine did not significantly reduce fresh weight only at the 1/2× rate at the mid1- and mid2-POST stages. Differences in fresh weight between all herbicide treatments and the non-treated control were not statistically significant at late-POST.

Only atrazine at both rates did not significantly reduce switchgrass fresh weight at the two- to three-leaf stage (early-POST, approximately 10 cm). Once switchgrass reached the two- to four-leaf stage (mid1- and mid2-POST, 20 to 30 cm), atrazine, prodiamine and acetochlor with or without atrazine did not significantly reduce fresh weight at the application rates tested (except acetochlor + atrazine at the 1× rate at the lower end of this range). However, biomass yields were reduced by as much as 40% with acetochlor treatments at the lower end of this growth stage. If sufficient PRE weed control can be achieved with atrazine (or perhaps quinclorac, imazethapyr, pendimethalin or imazapic) and switchgrass reaches the four- to five-leaf stage (late-POST, roughly 60 cm), then all tested POST-applied herbicides may be viable options for PRE or POST weed control. In addition, pendimethalin, a microtubule assembly disruptor similar to prodiamine, produced similar results to prodiamine when applied POST (same rates as were applied in the PRE experiment) to both switchgrass and prairie cordgrass (unpublished data).

With prairie cordgrass, 2,4-D ester at both rates and nicosulfuron and quinclorac at the 1/2× rate did not significantly reduce fresh weight at the two- to three-leaf stage (early-POST, approximately 15 cm). At the three- to five-leaf stage (mid1- and mid2-POST, roughly 30 to 40 cm), 2,4-D ester did not significantly reduce fresh weight at either rate, assuming the 1/2× rate data at mid1-POST were outliers. Wolf and Fiske (1995) suggested that 2,4-D or dicamba could be used to control broadleaf weeds during the year of establishment, but only after switchgrass has four fully expanded leaves, similar to recommendations for other perennial grasses (Scheinost et al. 2008). Atrazine, nicosulfuron, quinclorac and prodiamine may also be potential candidates, although their impact on prairie cordgrass growth was variable at this stage. If weeds can be controlled PRE with quinclorac, sulfosulfuron or pendimethalin until the five- to six-

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Table 5. Herbicide injury, plant height and fresh weight of prairie cordgrass as percentages of the non-treated controls following POST treatments at two herbicide rates and four growth stages.

	Rate	Growth stage[a]							
Herbicide treatment	kg ai (ae) ha^{-1}	Early-POST		Mid1-POST		Mid2-POST		Late-POST	
Injury[b,c]									
Non-treated control	—	100	A	100	A	100	A	100	A
2,4-D[d]	0.267 (ae)	100	A	100	A	100	A	83	A
	0.533 (ae)	100	A	100	A	100	A	100	A
Acetochlor	0.835	4	E	100	A	35	B	100	A
	1.67	0	E	96	AB	31	BC	100	A
Acetochlor + atrazine	0.835 + 0.562	0	E	88	B	31	BC	92	A
	1.670 + 1.123	0	E	75	BC	17	C	100	A
Atrazine	0.842	63	C	100	A	100	A	96	A
	1.684	23	D	67	C	100	A	100	A
Nicosulfuron[e]	0.018	100	A	96	AB	100	A	88	A
	0.035	79	B	88	B	96	A	83	A
Prodiamine	0.369	79	B	100	A	88	A	92	A
	0.737	79	B	100	A	96	A	96	A
Quinclorac[f]	0.14	100	A	100	A	96	A	88	A
	0.279	100	A	100	A	96	A	96	A
Plant height[g]									
Non-treated control	—	100 (77)	A	100 (93)	AB	100 (89)	AB	100 (103)	A
2,4-D[d]	0.267 (ae)	82	AB	90	BCDE	104	A	91	AB
	0.533 (ae)	92	AB	100	AB	102	AB	99	A
Acetochlor	0.835	14	DE	82	BCDE	39	C	88	AB
	1.67	0	E	70	DE	32	CD	72	B
Acetochlor + atrazine	0.835 + 0.562	2	E	84	BCDE	37	CD	77	B
	1.670 + 1.123	0	E	75	CDE	19	D	77	B
Atrazine	0.842	49	C	96	ABC	97	AB	105	A
	1.684	29	D	67	E	89	AB	94	AB
Nicosulfuron[e]	0.018	95	A	99	AB	105	A	95	AB
	0.035	76	B	94	ABC	104	A	95	AB
Prodiamine	0.369	84	AB	99	AB	73	B	92	AB
	0.737	74	B	93	ABC	84	B	94	AB
Quinclorac	0.14	91	AB	106	A	96	AB	89	AB
	0.279	86	AB	106	A	87	AB	99	A
Fresh weight[g]									
Non-treated control	—	100 (8.53)	A	100 (11.20)	A	100 (13.81)	A	100 (10.93)	AB
2,4-D[d]	0.267 (ae)	76	AB	65	DEF	84	AB	94	B
	0.533 (ae)	75	AB	100	A	91	A	109	AB
Acetochlor	0.835	1	C	57	FG	17	C	81	B
	1.67	0	C	43	GH	13	C	81	B
Acetochlor + atrazine	0.835 + 0.562	0	C	62	EFG	13	C	96	AB
	1.670 + 1.123	0	C	25	H	3	C	77	B

Table 5. Continued.

Herbicide treatment	Rate	Growth stage[a]							
	kg ai (ae) ha^{-1}	Early-POST		Mid1-POST		Mid2-POST		Late-POST	
Atrazine	0.842	14	C	84	ABCD	71	AB	115	A
	1.684	3	C	55	FG	52	B	115	A
Nicosulfuron[e]	0.018	85	A	73	CDEF	89	A	106	AB
	0.035	58	B	41	GH	81	AB	101	AB
Prodiamine	0.369	57	B	78	BCDE	58	B	85	B
	0.737	58	B	74	BCDEF	69	B	94	B
Quinclorac	0.14	75	AB	95	AB	64	B	101	AB
	0.279	62	B	91	ABC	55	B	102	AB

[a] Growth stage of the plants at the time of treatment as outlined in Table 2.
[b] Herbicide injury was evaluated as the percent of green leaf and stem tissue for continuity of comparison.
[c] Letters denote groupings within columns for each growth stage, $\alpha = 0.05$.
[d] Includes ammonium sulfate @ 2.5% v/v.
[e] Includes nonionic surfactant @ 0.25% v/v.
[f] Includes methylated seed oil @ 1% v/v.
[g] Values in parentheses are the means for plant height (cm) and fresh weight (g).

leaf stage in prairie cordgrass (late-POST, approximately 65 cm), all tested POST-applied herbicides were shown to be safe with regards to biomass yield for PRE or POST weed control. Field testing is needed to confirm the results obtained from these greenhouse experiments.

These results show that viable PRE and POST herbicide options exist for weed control during establishment of switchgrass and prairie cordgrass. Although no options were identified that did not significantly reduce biomass yield in both grasses simultaneously, viable PRE options may include quinclorac and pendimethalin and viable POST options may include 2,4-D, nicosulfuron, quinclorac, prodiamine and pendimethalin in a mixture planting.

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