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Effects of Seeding Date and Weed Control on Switchgrass Establishment

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We tested the effects of seeding date and weed control during switchgrass establishment in a field experiment that was conducted in central Pennsylvania in 2007 and repeated in 2008. Switchgrass was no-till seeded in early May, late May, and mid-June, and three postemergence weed management treatments were evaluated, including Mow (only a single mowing), Broadleaf (2,4-D + dicamba), and Broad Spectrum (2,4-D + dicamba + atrazine + quinclorac). Switchgrass density increased at later seeding dates, except in 2008, when the middle seeding date had the lowest density. In both years, weed biomass in late summer was lowest in the last seeding date of the Broad Spectrum treatment. In contrast, switchgrass biomass in late summer was greatest in the first seeding date of the Broad Spectrum treatment in both years. In the year after establishment (production year), plots were split to test the effects of supplemental weed control, composed of metsulfuron + 2,4-D applied in May, on total aboveground yield. Supplemental control in the production year increased total aboveground yield in the Mow treatment only, indicating that effective weed control during the establishment year might reduce the need for weed control in the following year. Although maximum aboveground yield was achieved when switchgrass was seeded in May and herbicides were used, results from our experiment suggest that seeding switchgrass at a relatively high seeding rate in June in our study region and mowing annual weeds to reduce competition and prevent seed production could be an effective strategy if minimizing herbicide use is a priority.
Nomenclature: 2,4-D; atrazine; dicamba; quinclorac; switchgrass, *Panicum virgatum* L.
Key words: Bioenergy, integrated weed management, perennial forage, Pennsylvania.

Evaluamos los efectos de la fecha de siembra y el control de malezas durante el establecimiento de *Panicum virgatum* en un experimento de campo que se realizó en el centro de Pennsylvania en 2007 y se repitió en 2008. *P. virgatum* fue sembrado con cero labranza a principios y a finales de mayo y a mediados de junio y se evaluaron tres tratamientos posemergentes de manejo de malezas incluyendo chapia (solo un corte), aplicación de 2,4-D + dicamba para hoja ancha y aplicación de herbicidas de amplio espectro (2,4-D + dicamba + atrazine + quinclorac). La densidad de *P. virgatum* se incrementó en las siembras de fecha más tardías, excepto en 2008, cuando la fecha de siembra intermedia tuvo la densidad más baja. En ambos años, la biomasa de la maleza a fines del verano fue más baja con el tratamiento de amplio espectro con la última fecha de siembra. En contraste, la biomasa de *P. virgatum* fue la mayor al final del verano en el tratamiento de amplio espectro con la primera fecha de siembra en ambos años. En el año siguiente a su establecimiento (año de producción), las parcelas se dividieron para evaluar los efectos del control suplementario de malezas sobre el rendimiento total de biomasa aérea, realizando una aplicación de metsulfuron + 2,4-D en mayo. El control suplementario en el año de producción incrementó el rendimiento total de biomasa aérea solamente en el tratamiento con chapia, lo que indica que el control efectivo de malezas durante el año de establecimiento puede reducir la necesidad de control de malezas al año siguiente. Aunque el rendimiento máximo de biomasa aérea se logró cuando *P. virgatum* se sembró en mayo y se usaron herbicidas, los resultados de nuestro experimento sugieren que sembrar *P. virgatum* a una densidad relativamente alta en junio en nuestra región de estudio y chapear las malezas anuales para reducir la competencia y prevenir la producción de semillas, puede ser una estrategia efectiva si la prioridad es minimizar el uso de herbicidas.

Switchgrass is a perennial, warm-season bunchgrass native to tallgrass prairies and other regions in North America. Historically it has been grown in some areas of the United States for soil conservation and wildlife habitat, as a forage crop, and more recently for bioenergy (Sanderson et al. 2004). Potential energy uses are currently being investigated for switchgrass feedstocks, including cellulosic ethanol and combustion for heat (e.g., pellet stoves) and electricity (e.g., co-fired with coal) (McLaughlin and Kszos 2005; Parrish and Fike 2005). The potential to utilize switchgrass as a bioenergy crop has increased the need for information on a number of management issues, including appropriate seeding dates, seeding rates, and weed control, to increase the consistency of switchgrass establishment.

Limited research has been reported on the effects of switchgrass seeding date and, to the best of our knowledge, no research has investigated how delayed seeding might be used as a cultural weed management practice. Vassey et al. (1985) examined switchgrass emergence and yield from seeding dates that ranged from April to June in Iowa and reported emergence was more variable from year to year than from month to month within a year because of precipitation. Hsu and Nelson (1986) reported that switchgrass emergence in Missouri was more rapid in June than in April, and Sanderson et al. (1996) reported progressively better emergence from early April to mid-June in Virginia. In spite of the better emergence at the later dates, yields in Virginia during the first year were greater for the earlier seeding dates. Similar results were also observed in Pennsylvania; later seeded switchgrass yielded less and also had more weeds the year after seeding (Panciera and Jung 1984).

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The optimal time for switchgrass establishment in the northeast United States is unclear, but producers and land managers generally consider the last half of May and the first half of June to be a good target. A primary reason given for this later spring time frame is to ensure the soil is warm enough for more rapid seedling emergence and to avoid the peak emergence period for many summer annual weeds. Previous research determined that weed species exhibit specific patterns of emergence (Hartzler et al. 1999; Ogg and Dawson 1984; Stoller and Wax 1973). Hartzler et al. (1999) reported that common waterhemp (*Amaranthus rudis* Sauer), velvetleaf (*Abutilon theophrasti* Medicus), giant foxtail (*Setaria faberi* Herrm.), and woolly cupgrass [*Eriochloa villosa* (Thunb.) Kunth] displayed consistent emergence sequences during 3 yr of their experiment. Researchers in Pennsylvania classified eight different weed species as either early, middle, or late emerging species on the basis of planting of a spring crop (Myers et al. 2004). Delaying planting by as little as 7 to 14 d can greatly reduce weed–crop competition in some situations (Buhler and Gunsolus 1996), so the date of spring planting can determine the potential importance of different weed species.

Effective weed control during switchgrass establishment is critical for obtaining satisfactory stands and early biomass production (Buhler et al. 1998; Parrish and Fike 2005). Because switchgrass seed is relatively small and slow to germinate, switchgrass seedlings grow and establish slowly (Boydston et al. 2010; Buhler et al. 1998; Parrish and Fike 2005), and competition from weeds during the establishment period can be severe (Buhler et al. 1998). Weeds are often cited as a major reason for establishment failure (Boydston et al. 2010; Mitchell et al. 2010). If effective herbicides or other weed management tactics were available, earlier seeding dates might be beneficial, especially if maximum biomass production in the seeding year is a priority.

Dicamba and 2,4-D are registered for broadleaf weed control in perennial forage grasses, including switchgrass (Curran et al. 2008). A limitation for postemergence use of plant growth regulator herbicides in the establishment year is delaying application until perennial grass crops are well established and more herbicide tolerant (Curran et al. 2008). Compared with broadleaf weeds, grass weeds are more challenging to control selectively with herbicides in switchgrass (Boydston et al. 2010; Curran et al. 2009; Myers et al. 2006). Atrazine is used in some regions of the United States to control weeds in switchgrass (Bahler et al. 1984; Hintz et al. 1998; Martin et al. 1982), but its registration for this use has been cancelled in many states (Buhler et al. 1998). Quinclorac controls a number of annual broadleaf and grass weeds and was recently registered for use in switchgrass (Anonymous 2010). In a study that included three switchgrass cultivars and several herbicides, quinclorac was the most promising for annual grass control (Boydston et al. 2010), and a combination of quinclorac plus atrazine provided acceptable weed control for establishing both lowland and upland switchgrass cultivars in the Central and Northern Great Plains (Mitchell et al. 2010).

In addition to identifying herbicide options, research is needed on integrated approaches for managing weeds in switchgrass. Integrated weed management that includes physical and cultural practices during switchgrass establishment could be beneficial for several reasons. Management systems that employ multiple practices might be more resilient if one practice fails, thus reducing risk. The use of cultural weed management practices might reduce establishment costs and increase net returns compared with herbicide-based management programs. Cultural weed management practices could also be beneficial if switchgrass is grown in ecologically or environmentally sensitive areas where growers might want to reduce any potential nontarget effects from herbicides.

Once switchgrass has emerged and becomes established, mowing can provide switchgrass with a competitive advantage over weeds and prevent weed seed production (DiTomaso 2000). For most annual weed species, the optimum mowing time is the flowering stage before seed development. Annual grass weeds are generally not controlled as effectively as broadleaf species because of the location of crown buds in grasses, which is often beneath the height of mowing (Buhler et al. 1998). Although the effect of mowing on switchgrass performance has been investigated (Beaty and Powell 1976), the effectiveness of mowing for weed control during switchgrass establishment has not been reported.

The objective of this research was to evaluate the effects of seeding date and three different postemergence weed management tactics, including mowing, on weed control and switchgrass yield during the establishment year. Switchgrass performance was also evaluated in the year after establishment. Our first hypothesis was that mowing combined with a late seeding date would provide comparable weed control to using herbicides and seeding early. Our second hypothesis was that switchgrass biomass in the establishment year would be greatest with early seeding and effective weed control. Our third hypothesis was that effective weed control in the establishment year would negate any potential benefit from supplemental weed control in the production year.

Materials and Methods

A field experiment was conducted in 2007 to 2008 and repeated in 2008 to 2009 at the Penn State University Russell E. Larson Agricultural Research Center in Rock Springs, PA, (40°44′N, 77°57′W). Soil at the site was a Hagerstown silt loam (fine mixed, semiactive mesic Typic Hapludalfs) with a pH ranging from 6.5 to 6.7. The previous crop in 2006 was soybean, and in 2007 it was corn grown for grain. In 2008, corn residue was mowed, baled, and removed from the field before seeding. The upland switchgrass cultivar 'Cave-in-Rock' (Switchgrass seed, Ernst Conservation Seeds, 9006 Mercer Pike, Meadville, PA 16335) was no-till seeded in 18-cm rows at 13.5 kg ha^{-1} of pure live seeds on three separate dates ranging from early May to mid-June (Table 1). Seed was scarified as described by Shen et al. (2001) to ensure maximum germination. Before switchgrass emergence, glyphosate (Roundup WeatherMax®, containing glyphosate 540 g ae L^{-1}, Monsanto Co., 800 North Lindbergh Boulevard, St. Louis, MO 63167) at 0.84 kg ae ha^{-1} was applied as a burndown to control emerged vegetation across

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Table 1. Dates of management practices and sampling activities. Note that "Year" represents the year that switchgrass was established.

Year	Event	Early	Middle	Late
2007	Seeding	May 4, 2007	May 21, 2007	June 7, 2007
	Burndown	May 7, 2007	May 23, 2007	June 7, 2007
	Stand counts	June 14, 2007	June 29, 2007	July 10, 2007
	Postemergence herbicide	June 14, 2007	June 29, 2007	July 10, 2007
	Mow	July 10, 2007	August 1, 2007	August 13, 2007
	Biomass sampling	August 23, 2007	August 23, 2007	August 23, 2007
	Harvest establishment year	October 31, 2007	October 31, 2007	October 31, 2007
	Supplemental control	May 6, 2008	May 6, 2008	May 6, 2008
	Harvest production year	November 7, 2008	November 7, 2008	November 7, 2008
2008	Seeding	May 1, 2008	May 23, 2008	June 19, 2008
	Burndown	May 2, 2008	May 26, 2008	June 20, 2008
	Stand counts	July 2, 2008	July 11, 2008	July 28, 2008
	Postemergence herbicide	July 2, 2008	July 11, 2008	July 28, 2008
	Mow	July 22, 2008	July 28, 2008	August 18, 2008
	Biomass sampling	September 16, 2008	September 16, 2008	September 16, 2008
	Harvest establishment year	November 7, 2008	November 7, 2008	November 7, 2008
	Supplemental control	May 12, 2009	May 12, 2009	May 12, 2009
	Harvest production year	October 26, 2009	October 26, 2009	October 26, 2009

all treatments (Table 1). In 2008, 2,4-D LVE (Weedone® LV4 EC, containing 2,4-D isooctyl ester 67%, Nufarm Americas Inc., 1333 Burr Ridge Parkway, Suite 125A, Burr Ridge, IL 60527) at 0.28 kg ae ha^{-1} was included in the burndown to help control emerged dandelion (*Taraxacum officianale* G. H. Weber ex Wiggers). Experiments were not irrigated and precipitation during the 2007, 2008, and 2009 growing seasons (April to November) was 535, 588, and 597 cm, respectively.

The experiment was arranged as a split plot randomized complete block with four replications, and individual split plots measured 4.6 by 9 m. Switchgrass seeding date was the main plot factor, and weed control was the split plot factor. Three weed control treatments were included: Mow, Broadleaf, and Broad Spectrum. In the Mow treatment, plots were mowed to a height of 30 cm at 8 to 10 wk after seeding (WAS). In the Broadleaf treatment, 2,4-D amine (Weedar® 64, containing 2,4-D dimethylamine salt 47%, Nufarm Americas Inc.) at 0.28 kg ae ha^{-1} + dicamba (Clarity®, containing dicamba, diglycolamine salt of 3,6-dichloro-*o*-anisic acid 480 g L^{-1}, BASF Corporation, 26 Davis Drive, Research Triangle Park, NC 27709) at 0.28 kg ae ha^{-1} were applied about 6 WAS. In the Broad Spectrum treatments, atrazine (Aatrex® 4L, containing atrazine 479 g L^{-1}, Syngenta Crop Protection, P.O. Box 18300, Greensboro, NC 27419) at 1.1 kg ai ha^{-1} + 2,4-D amine at 0.28 kg ha^{-1} + dicamba at 0.28 kg ha^{-1} + quinclorac (Paramount®, containing quinclorac 0.75 kg kg^{-1}, BASF Corporation) at 0.42 kg ai ha^{-1} + 0.25% (v/v) non-ionic surfactant were applied about 6 WAS. The Mow treatment represented the minimum level of weed management that would be required to establish switchgrass. The Broadleaf herbicide treatment represented an intermediate level of control and is more typical of management commonly used in the study region, whereas the Broad Spectrum treatment represented a high level of control and included herbicides not labeled for use in switchgrass at the time of the experiment.

In 2007 only, atrazine in the Broad Spectrum treatment was applied preemergence to the switchgrass and weeds rather than with the postemergence treatment. However, because of concern for injury, atrazine was applied postemergence in 2008 in combination with the other herbicides. Atrazine was included in this experiment because of its known utility and long history of controlling weeds in warm-season grasses (Bahler et al. 1984; Hintz et al. 1998; Martin et al. 1982). Herbicides were applied with a hand-held CO_2 backpack sprayer with water at 187 L ha^{-1} at 207 kPa. Switchgrass was 15 to 20 cm tall with three to four leaves, whereas annual weeds were 15 to 25 cm at the 6 WAS application. By 10 WAS, switchgrass was 35 to 45 cm tall and the weeds were 40 to 60 cm tall.

Switchgrass tiller density data were collected from two 0.5-m^2 quadrats per plot about 4 WAS before any weed management (Table 1). Aboveground plant biomass was collected from two 0.5-m^2 quadrats per plot in late summer (Table 1), separated into weeds and switchgrass, and oven dried at 55 C for at least 72 h and weighed. Total aboveground yield (switchgrass and weeds) was collected in late October or early November of each year (Table 1) by removing a 1.5-m-wide by 9-m-long swath using a small plot forage harvester (Model 212 small plot harvester, Hege Equipment Inc., 13915 W 53rd Street North, Colwich, KS 67030) and weighing. A subsample (c. 1,000 g) of biomass was removed from each harvested plot, weighed, dried at 55 C for at least 72 h, and weighed again to determine moisture content.

In the year after establishment (production year), 84 kg ha^{-1} N was broadcast applied in late May of 2008 and 2009 to the entire experiment to ensure adequate fertility. Split plots were split again in the production year to test the effects of supplemental weed control in the year after establishment. Split-split plots either received no additional weed control or they received an application of metsulfuron (Cimarron® 60DF, metsulfuron 60%, Dupont Co., 1007 Market Street Wilmington, DE 19898) at 0.084 kg ai ha^{-1} + 2,4-D amine at 0.56 kg ha^{-1} + 0.25% (v/v) non-ionic surfactant in early May of the production year when switchgrass was 15 cm tall (Table 1). Metsulfuron and 2,4-D were tested because they are commonly used in the study region for weed control in perennial grass forage crops (Curran et al. 2008). In late October 2008 and early November 2009, total aboveground yield (switchgrass and

Table 2. Effects of seeding date and control method on switchgrass density, switchgrass biomass, weed biomass, and total aboveground yield in 2007 (upper) and 2008 (lower).

Year	Effect	Switchgrass density[a]		Switchgrass biomass		Weed biomass		Total aboveground yield	
2007	Date	***		—		**		*	
	Control	—		***		***		***	
	Date × Control	—		*		—		*	
	Treatment means[b]	tlrs m^{-2}		g m^{-2}		g m^{-2}		kg ha^{-1}	
	Mow	316		57 c		92 a		1,462 b	
	Broadleaf	285		86 b		68 a		1,876 ab	
	Broad spectrum	271		132 a		30 b		2,274 a	
	Regression slopes[c]	tlrs m^{-2} day^{-1}	r^2	g m^{-2} day^{-1}	r^2	g m^{-2} day^{-1}	r^2	kg ha^{-1} day^{-1}	r^2
	Date	7.5	0.67***	—	—	−1.7	0.27***	—	—
	Mow × Date	—	—	0.5	0.04	—	—	−3.2	0.01
	Broadleaf × Date	—	—	−0.3	0.01	—	—	−14.2	0.14
	Broad spectrum × Date	—	—	−2.8	0.78***	—	—	−38.3	0.55**
2008	Date	***		**		*		***	
	Control	—		**		***		***	
	Date × Control	—		**		—		—	
	Treatment means	tlrs m^{-2}		g m^{-2}		g m^{-2}		kg ha^{-1}	
	Mow	260		235 b		75 a		1,703 b	
	Broadleaf	236		310 a		60 a		2,129 a	
	Broad spectrum	305		286 ab		24 b		1,756 b	
	Regression slopes	tlrs m^{-2} day^{-1}	r^2	g m^{-2} day^{-1}	r^2	g m^{-2} day^{-1}	r^2	kg ha^{-1} day^{-1}	r^2
	Date	1.5	0.05	—	—	−0.7	0.07	−20.9	0.55***
	Mow × Date	—	—	−1.8	0.24	—	—	—	—
	Broadleaf × Date	—	—	−2.1	0.33*	—	—	—	—
	Broad spectrum × Date	—	—	−5.4	0.77***	—	—	—	—

[a] tlrs, tillers. Switchgrass density was measured before control treatments were applied; thus, weed control and the seeding date by control interaction were excluded from the ANOVA.

[b] Similar letters next to treatment means indicate no significant difference ($P < 0.05$).

[c] Results from the ANOVA guided the regression analysis, such that control treatments were pooled (common slope) with no interaction. When an interaction occurred, separate regression models were fit for each of the three control treatments (e.g., Mow × Date).

* Significantly different at $\alpha = 0.05$ (*F* test).

** Significantly different at $\alpha = 0.01$ (*F* test).

*** Significantly different at $\alpha = 0.002$ (*F* test).

weeds) was collected as previously described to assess the effects of supplemental control and to test for residual effects from the establishment year treatments (Table 1).

Statistical Analyses. Analyses were performed with SAS 9.2 (statistical analysis software, SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513). Switchgrass density and biomass, weed biomass, and total aboveground yield data were subjected to ANOVA to test for treatment differences. Seeding date was included as a categorical variable in the ANOVA because we only tested three dates. Although analysis of covariance was an option, our approach appropriately describes the effects of the experimental factors without forcing a linear relationship between seeding date and response variables (e.g., switchgrass density). Instead, if the ANOVA indicated a significant seeding date effect or if there was a seeding date by control treatment interaction, then we used linear regression to analyze the effects of seeding date on response variables. This provided an efficient method for assessing the effect of seeding date. All data were log-transformed before analysis to conform to the assumption of homogeneous variance, except for total aboveground yield. Data were not transformed for regression analyses so that slopes between dependent variables and seeding date would be interpretable. We used nonlinear regression to test the effect of switchgrass density on weed biomass by fitting the following hyperbolic model,

$$W = w_0\{1/[1 + (i \times S)]\}$$

where W is weed biomass (g m^{-2}), w_0 is the intercept (g m^{-2}), i is the switchgrass competition coefficient (m^2 $tiller^{-1}$), and S is switchgrass density (tillers m^{-2}). The weed suppressive effect of switchgrass was expressed as the parameter i, which describes the fractional reduction in weed biomass per switchgrass tiller. Curves were plotted with SigmaPlot 11.0 (graphing software, Systat Software Inc., 1735 Technology Drive, Suite 430 San Jose, CA 95110). We tested for differences in total aboveground yield in the year after switchgrass establishment using a split-split plot model with seeding date as the main plot, control method as the split plot, and supplemental control as the split-split plot. Treatment means were compared with the Tukey–Kramer method. Significance was set at $P = 0.05$; however, we refer to effects at $P < 0.1$ as marginally significant.

Results and Discussion

Switchgrass Density and Biomass. Results are presented for each establishment year separately because of several

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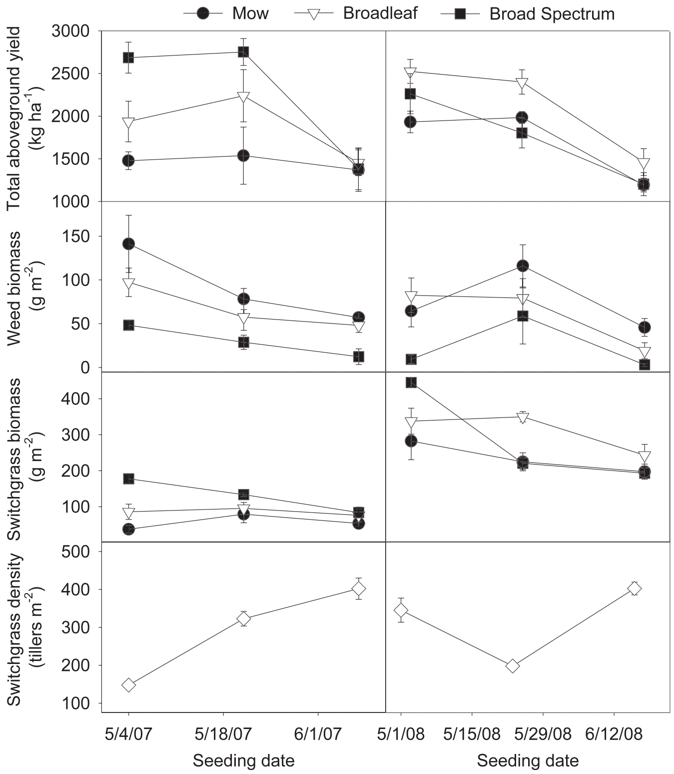

Figure 1. Mean total aboveground yield, weed biomass, switchgrass biomass, and switchgrass density in control treatments over seeding dates in 2007 (left) and 2008 (right). Bars represent standard errors. Switchgrass density data were pooled across weed control treatments because sampling was done before implementation of weed control treatments. Note that all *y*-axes do not start at zero.

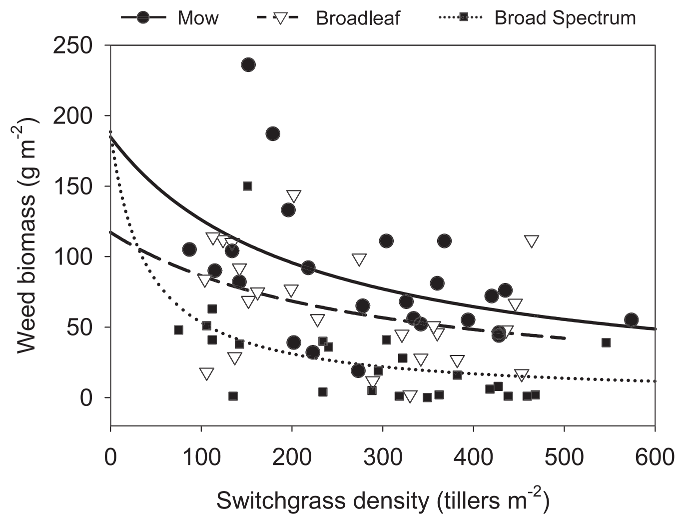

Figure 2. Weed biomass as a function of switchgrass density during the establishment year in each control treatment. Data were pooled over seeding dates and years for this analysis. Results for each treatment are as follows: Mow, w_0 = 185 g m^{-2}, i = 0.0047 m^2 tiller^{-1} (P = 0.024, r^2 = 0.21); Broadleaf, w_0 = 117 g m^{-2}, i = 0.0036 m^2 tiller^{-1} (P = 0.068, r^2 = 0.14); Broad spectrum, w_0 = 189 g m^{-2}, i = 0.0254 m^2 tiller^{-1} (P = 0.012, r^2 = 0.25).

interactions between year and treatment factors. Switchgrass density increased with the delay in seeding in 2007, whereas in 2008, density was lowest at the second seeding date and greatest at the last date (Table 2; Figure 1). Our results are congruent with previous research that reported faster or more consistent emergence with later seeding dates (Hsu and Nelson 1986). In 2008, we applied 2,4-D with glyphosate in the burndown application to aid in the control of dandelion just after switchgrass seeding. After the second seeding on May 23, a cool period with nighttime temperatures down to 3 C persisted for the following week. We speculate that 2,4-D injury contributed to the reduction in switchgrass density at the second seeding date in 2008. The potential for warm-season grass injury from 2,4-D and other phenoxy-type herbicides seems to vary, with no injury being reported in some research (Washburn and Barnes 2000) to moderate or severe injury reported elsewhere (Bovey and Hussey 1991; Lair and Redente 2004). These results suggest that preemergence 2,4-D applications to switchgrass could require additional precautions, such as delayed crop planting after application, as is suggested for both corn (*Zea mays* L.) and soybean (*Glycine max* L.) (Anonymous 2007).

Switchgrass biomass was greater in 2008 compared with 2007 (Figure 1), which might have been a result of the later sampling in 2008 (about 3 wk later), which allowed greater switchgrass biomass accumulation (Table 1). Both years saw a seeding date by control method interaction because switchgrass biomass was greatest in the Broad Spectrum treatment at the early seeding date but was not different from the Broadleaf or Mow treatments at the last seeding date (Table 2; Figure 1). The relatively low switchgrass biomass in the Mow treatment was expected given the short duration of time between mowing and biomass sampling (Table 1).

Weed Control. The primary weeds in this experiment were yellow foxtail [*Setaria glauca* (L.) Beauv.] and smooth pigweed (*Amaranthus hybridus* L.). Average weed biomass was lowest in the last seeding date compared with the two earlier seeding dates and was lowest for the Broad Spectrum treatment compared with the Mow and Broadleaf treatments (Table 2; Figure 1). Average weed biomass in the Mow treatment at the last seeding date (57 and 46 g m^{-2} in 2007 and 2008, respectively) was lower than in the Broadleaf treatment (97 and 83 g m^{-2} in 2007 and 2008, respectively) but greater than in the Broad Spectrum treatment (48 and 9 g m^{-2} in 2007 and 2008, respectively) at the first seeding date. This result partially supports our first hypothesis, in that weed biomass in the Mow treatment combined with late seeding would be comparable to the herbicide treatments applied to early-seeded switchgrass.

In 2008, mean weed biomass was greater in the middle seeding date (85 kg ha^{-1}) compared with the early (52 kg ha^{-1}) and late (23 kg ha^{-1}) seeding date. The lower switchgrass tiller density in the middle seeding date likely reduced the competitive ability of the crop and allowed for increased weed growth. Although we did not originally intend to test the effects of switchgrass density on weed suppression, the 2,4-D injury in the middle seeding date in 2008 and resulting decrease in switchgrass density prompted us to test the relationship between weed biomass and switchgrass

Table 3. Ratios of switchgrass biomass (g m^{-2}) to weed biomass (g m^{-2}) across switchgrass seeding dates and weed control treatments in 2007 and 2008.[a] Similar letters indicate no significant difference between control treatments within a year.

			Switchgrass biomass to weed biomass		
Year	Control treatment	$P < 0.05$	Early	Mid	Late
2007	Mow	b	0.3	1.0	0.9
	Broadleaf	b	0.9	1.7	1.6
	Broad Spectrum	a	3.7	4.7	6.9
2008	Mow	b	4.4	1.9	4.3
	Broadleaf	b	4.1	4.4	12.8
	Broad Spectrum	a	48.1	3.8	64.4

[a] Switchgrass biomass and weed biomass were sampled from the same quadrats on August 23, 2007, and September 16, 2008. ANOVA showed no interaction between seeding date and weed control treatment; however, data are presented at the interaction level for completeness.

density (Figure 2). The weed suppressive effect of increasing switchgrass density is represented by the switchgrass competition coefficient i, which was 0.0047, 0.0036, and 0.0254 m^2 $tiller^{-1}$ for the Mow, Broadleaf, and Broad Spectrum treatments, respectively. These results demonstrate the importance of adequate seedling density for weed suppression and suggest that increasing seeding density of switchgrass might be an effective cultural weed management practice that could compliment mowing and delayed seeding. Previous research has examined switchgrass seeding rates and concluded that 4 to 10 kg ha^{-1} is generally adequate (Moser and Vogel 1995; Vassey et al. 1985; Vogel 2000). Although considerable plasticity or compensatory yield exists within the species (Parrish and Fike 2005), the relationship between weed competition and seeding rate deserves greater attention.

Weed control and switchgrass performance were evaluated simultaneously by calculating the ratio of switchgrass biomass to weed biomass for weed control treatments at each seeding date in 2007 and 2008 (Table 3). In general, ratios for both switchgrass biomass and total aboveground yield were greatest in the Broad Spectrum treatment at the late seeding date. The effect of weed control treatment on the ratio of switchgrass biomass to weed biomass was significant in 2007 ($P = 0.002$) and 2008 ($P < 0.001$). The effect of seeding date on the ratio of switchgrass biomass to weed biomass was marginally significant ($P = 0.061$) in 2007, and the decreased switchgrass density in the middle planting date in 2008 could have limited our ability to detect differences in 2008 (Table 3). This indicates that although early seeding might maximize switchgrass biomass, late seeding has the potential to result in a greater proportion of switchgrass to weed biomass, which might be desirable depending on the end use.

Total Aboveground Yield. Seeding date and weed control treatments were also evaluated in terms of total aboveground yield, which included both switchgrass and weeds. These values are comparable to the end product that would be used commercially for biomass energy. Total aboveground yield was measured with a plot combine in early November, compared with the switchgrass biomass and weed biomass that were sampled 6 to 10 wk earlier.

Establishment Year. In general, total aboveground yield during the establishment year was lowest at the later seeding dates and in the Mow treatment (Figure 1). Plots established in 2007 had a seeding date by weed control treatment interaction in which total aboveground yield was greatest in the Broad Spectrum, lower in the Broadleaf, and lowest in the Mow treatment for the first two seeding dates. Total aboveground yield decreased substantially in the two herbicide treatments at the last seeding date and was not different from the Mow treatment. Despite greater switchgrass density and lower weed biomass at the last seeding date, switchgrass yields were 38 to 43% lower than the middle and early dates, respectively. In 2007, the greatest yield across control treatments was in the Broad Spectrum treatment, whereas in 2008, the greatest yield was in the Broadleaf treatment (Table 2). These results support our second hypothesis that the greatest total aboveground yield would be obtained with the early seeding date treatment for which weeds were effectively controlled.

Production Year. In the year after establishment (production year), plots were monitored for legacy effects from the establishment year and split to test the effects of supplemental weed control, composed of metsulfuron and 2,4-D applied in May (Table 1), on total aboveground yield. Total aboveground yield was not different across seeding dates in 2008 (Table 4). However, in 2009, plots that were seeded later in the previous year yielded less than plots that were seeded earlier (Figure 3). The negative relationship with planting date and total aboveground yield in the following year was

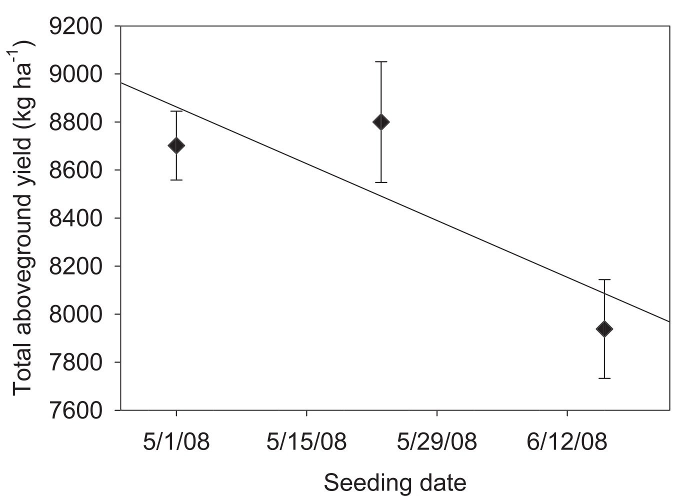

Figure 3. Total aboveground yield in the year after establishment across 2008 seeding dates. Note that the y-axis does not start at zero. Bars represent standard errors.

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Table 4. Results from ANOVA on total aboveground yield (kg ha^{-1}) in the year after switchgrass establishment.

Effect	2007	2008
Date	-	**
Control	***	**
Date × Control	—	—
Supplemental	***	*
Date × Supplemental	—	—
Control × Supplemental	***	—
Date × Control × Supplemental	—	—

	Supplemental			
	2007		2008	
Control	With	Without	With	Without
Mow	7,028 b	5,782 c	7,978 b	8,055 b
Broadleaf	7,830 ab	7,319 ab	8,524 ab	8,854 ab
Broad spectrum	8,347 ab	8,479 ab	8,362 a	9,107 a

* Significantly different at $\alpha = 0.1$ (F test).

** Significantly different at $\alpha = 0.05$ (F test).

*** Significantly different at $\alpha = 0.001$ (F test).

significant ($y = 10{,}923 - 17x$, where y = total aboveground yield [kg ha^{-1}] and x = day of year; P = 0.01, $r^2 = 0.1$). In both production years (2008 and 2009), total aboveground yield was lower in the Mow treatment than in the Broad Spectrum treatment (Table 4). Taken together our results indicate that seeding date and weed control during switchgrass establishment can have an effect on total aboveground yield in the production year, which is congruent with previous research that reported effective weed control during the establishment year can increase yields in subsequent years (Martin et al. 1982; Vogel 1987).

In 2008, an interaction between weed control treatments applied in 2007 and the supplemental control treatment applied in 2008 affected total aboveground yield. Supplemental control did not affect total aboveground yield in the production year in both the Broadleaf and Broad Spectrum treatments. However, in the Mow treatment, total aboveground yield in the production year was greater with supplemental control (Table 4). In 2008, treatments that provided effective weed control during the establishment year did not benefit from the supplemental herbicide application in the year after establishment (i.e., the first production year). In 2009, the effect of supplemental control was marginally significant (Table 4; P = 0.066; P= 0.055 when nonsignificant interactions were removed from the ANOVA model, not shown). The difference between years might be related to more dandelion in the spring 2008, whereas relatively few perennial weeds were present in spring 2009 (personal observation, data not shown). These results support our third hypothesis that effective weed control in the establishment year would negate any benefit of supplemental weed control the year after establishment.

Overall, switchgrass density and weed suppression were greatest for the last seeding date. However, the greatest switchgrass yields were observed when it was seeded earlier and herbicides were applied. Despite greater yields with earlier seeding, the ratio of switchgrass to weed biomass was greatest in the last seeding date, indicating that delayed seeding could result in higher quality yield. Supplemental weed control during the production year provided a yield benefit when herbicides were not used in the establishment year. On the other hand, mowing in combination with seeding switchgrass in late spring reduced weed biomass and could be a viable strategy for producers wanting to minimize herbicide use during establishment.

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