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Effects of Giant Foxtail (*Setaria faberi*) and Yellow Foxtail (*Setaria pumila*) Competition on Establishment and Productivity of Switchgrass

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Switchgrass is a potential feedstock for cellulosic bioenergy production. Weed competition from annual grass during the establishment year can reduce switchgrass establishment and resulting productivity, but the relationship between early season grass densities and outcomes of competition are not well understood. We measured how a range of giant and yellow foxtail densities in the establishment year influenced switchgrass establishment and resulting productivity in the first production year (second year of the growing season). In two of the three site–yr more than four foxtail plants m^{-2} reduced switchgrass plant densities below documented thresholds of establishment success. A lesser effect of foxtails in the third site–year suggested that higher switchgrass emergence rates reduced foxtail competitive ability during establishment. Effects on yield were consistent over the three site–yr. The yield (10.96 Mg $ha^{-1} \pm 0.77$) decreased rapidly as foxtail density increased. One foxtail plant m^{-2} reduced switchgrass yield in the first production year by 25%, and yield loss was 90% or greater at densities > 50 foxtail plants m^{-2}. Although switchgrass can establish in the presence of foxtail competition, these weed species should be controlled to maximize yields in the first production year.

Nomenclature: Giant foxtail, *Setaria faberi* Herrm.; yellow foxtail, *Setaria pumila* (Poir.) Roemer & J.A. Schultes; switchgrass, *Panicum virgatum* L.

Key words: Biofuels, cellulosic biofeedstocks, crop–weed competition, rectangular hyperbolic yield loss, weed density.

Federal policy is encouraging increased bioenergy production, including biofuels from cellulosic biomass (US Congress 2007). Switchgrass is a promising bioenergy feedstock because of its ability to grow in a range of environments (Vogel 1996, 2004) and the environmental benefits it offers over annual cropping systems (Blanco-Canqui 2010; Fletcher et al. 2011; Lee et al. 2007; Liebig et al. 2008; Robertson et al. 2011; Wu et al. 2012). Although productive and competitive, with minimal inputs once established, weed competition can impede establishment success and resulting productivity (Fike et al. 2006; Mitchell et al. 2008; Parrish and Fike 2005; Schmer et al. 2006; Vogel 1996, 2004).

Annual grass weeds, in particular, are a concern when establishing switchgrass in agronomic fields (Boydston et al. 2010; Curran et al. 2009; Kering et al. 2013; Myers et al. 2006; Parrish and Fike 2005). In the midwestern United States, warm-season (C_4) annual grasses emerge before or as switchgrass seedlings emerge, have much faster growth rates (Hsu et al. 1985), and are abundant in agronomic fields (Fickett et al. 2013a,b). Herbicides that have activity on annual grasses and have been tested for use during switchgrass establishment can injure switchgrass (Boydston et al. 2010; Kering et al. 2013; Mitchell et al. 2010; Renz 2011; Wilson 1995). Although broadleaf weeds are also a concern, a range of herbicides are available that effectively suppress populations during establishment (Boydston et al. 2010; Curran et al. 2009; Myers et al. 2006).

Annual grass competition during switchgrass establishment has been linked to reductions in switchgrass establishment and yields. For example, Miesel et al. (2012) found that herbicide treatments that reduced annual grass cover 61% in the establishment year resulted in 45% higher yield the year after planting compared with an at-planting application of glyphosate. However, Curran et al. (2012) found that although a herbicide treatment that controlled both grass and broadleaf weeds in the establishment year reduced weed biomass $> 50\%$, switchgrass biomass was not increased in the first production year compared with a broadleaf herbicide treatment alone. Thus, there is evidence that some annual grass competition may be tolerated when establishing switchgrass, but the amount of competition that can be tolerated is not known.

The ability to predict yield loss based on weed competition is critical to making weed management

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decisions (Cousens 1985; Mortimer and Firbank 1983). The relationship between annual grass competition during the establishment year and switchgrass yield loss in the first production year requires further investigation to inform establishment-year weed-management decisions. Weed density is a common variable used to estimate yield loss from weed competition (Firbank et al. 1990; Whish et al. 2002), and yield loss models have been used to predict yield losses based on early season weed densities (Fast et al. 2009; Fickett et al. 2013a,b; Jeschke et al. 2011; Murphy et al. 2002; Tamado et al. 2002; Whish et al. 2002). In this article, we examine the effect of a range of yellow and giant foxtail densities on (1) switchgrass establishment success, and (2) biomass yield in the first production year, using data from 3 site–yr across south-central Wisconsin.

Materials and Methods

Site Description. Field experiments were conducted from 2011 to 2012 at the University of Wisconsin Arlington Agricultural Research Station, Arlington, WI (43.308056°N, 89.348056°W), and 2011 to 2013 at the University of Wisconsin Rock County Farm near Janesville, WI (42.726111°N 89.025 278°W). The Arlington experimental site was previously planted in glyphosate-resistant corn (*Zea mays* L.), and the Janesville site was previously planted in perennial grasses commonly found in the Conservation Reserve Program. The soil type at both sites was Plano silt loam. Soil pH before establishment was 6.3 at the Arlington site and 7.3 at the Janesville site. The soil at the Arlington site was 3.4% organic matter, with 34 ppmw P and 105 ppmw K. The soil at the Janesville site was 6.1% organic matter, with 331 ppmw P and 701 ppmw K.

Weed community composition was assessed throughout summer of 2011 and 2012. The Arlington site included giant foxtail, common ragweed (*Ambrosia artemisiifolia* L.), common lambsquarters (*Chenopodium album* L.), dandelion (*Taraxacum officinale* G.H. Weber ex Wiggers), and large crabgrass [*Digitaria sanguinalis* (L.) Scop.]. At the Janesville site, giant foxtail, fall panicum (*Panicum dichotomiflorum* Michx.), and jimsonweed (*Datura stramonium* L.) were dominant in 2011, whereas giant and yellow foxtail and common purslane (*Portulaca oleracea* L.) were dominant in 2012. Little mallow (*Malva parviflora* L.) was prevalent in both years at Janesville.

Experiment Establishment and Maintenance. Experimental plots were established at the Arlington site in 2011 and at the Janesville site in 2011 and 2012 and were harvested at the end of the first production year (second growing season). 'Cave-in-Rock' variety of switchgrass (Heritage Seed Company, Madison WI) was planted in mid to late May into tilled fields with a prepared seedbed using a Brillion seeder (Brillion Farm Equipment, Brillion, WI). Switchgrass was planted to achieve a seeding rate of 11.2 kg pure live seed (PLS) ha^{-1}. After seeding switchgrass, an equal mixture of locally collected giant and yellow foxtail (hereafter, *foxtail*) seeds were scattered by hand evenly throughout each plot to achieve the target density of foxtail for that plot. For each plot, a target density was randomly assigned within the specified target range of either 5 to 15, 30 to 50, 70 to 90, or 91 to 100 plants m^{-2} as well as a weed-free control, and an in situ control with no added foxtail seeds. To achieve the target foxtail density in each plot, four times the target number of seeds, which had a germination rate of 25%, were scattered throughout the plot. After foxtail seeds were scattered, another pass was made over the entire experiment with the Brillion seeder containing no seed to ensure good seed–soil contact and a firm seedbed. To maintain the target foxtail densities throughout the growing season, plots were hand-weeded weekly to the target density for the first month after seeding, and subsequently at 2-wk intervals until the end of August. Annual grasses in the in situ control plots were not weeded to a specific density. Broadleaf weeds were removed throughout the establishment year from all plots when foxtail populations were thinned. Weeding was accomplished by clipping weeds at the soil surface.

Fertilizer was not applied at any of the locations during the course of the study. 2,4-D ester was broadcast applied at 1 kg ae ha^{-1} in May of each production year (2012 and 2013) at the Janesville site for broadleaf weed control. The Arlington site was relatively free of broadleaf weeds in the production year ($<$ 10% cover), so 2,4-D was not applied.

Experimental Design. A randomized complete-block design with four blocks was used to assess the effects of foxtail density on relative cover of switchgrass in the fall of the establishment year, switchgrass density in the spring of the production year, and biomass yield of switchgrass in September of the production year. Plots were 1 m by 1 m with a 2-m grass border between plots. Densities (0 to 100 plants m^{-2}) were chosen to represent the range of foxtail densities found in Wisconsin's agricultural fields (Fickett et al. 2013a,b) but within distinctive weed density categories (0, 5 to 15, 30 to 50, 70 to 90, and 91 to 100 PLS m^{-2}). For each plot, a target density was randomly selected within the range class assigned to the plot resulting in 16 unique densities and four weed-free plots at each site.

Measurements. Switchgrass cover in the fall of the establishment year and switchgrass density in the spring of the first production year were measured to assess establishment success. Switchgrass cover in the fall of the establishment year has been correlated with yield in the first production year (Renz et al. 2012), and switchgrass density in the spring is a common measure used to assess stand success (Launchbauch and Owensby 1970). Switchgrass and annual grass relative cover were visually estimated in September of the establishment year. Switchgrass density was estimated in each plot on May 15 of the production year by randomly tossing three 0.093-m^2 quadrats into each plot. Productivity was measured by harvesting the plots in September of the production year after seed dehiscence but before the first frost. Plots were harvested using a sickle-bar mower set at a 15-cm residual height. Switchgrass was separated from weeds (broadleaves and grasses), and both were dried for at least three wk at > 55 C before being weighed. Precipitation and temperature data were obtained from nearby weather stations for both sites over the course of each growing season during switchgrass establishment years 2011 and 2012.

Statistical Analysis. *Regression Analysis.* We used regression analysis to determine the relationship between early season foxtail density and switchgrass establishment success, as measured by switchgrass cover in the fall of the establishment year and switchgrass density in spring of the first production year. We fit a series of two-parameter concave functions (Ratkowsky 1990), and chose the model with the best fit (Equation 1: fall switchgrass cover; Equation 2: spring switchgrass density), as determined by a combination of visual assessment of the residuals, normality, and residual standard error.

$$\textit{Fall switchgrass cover} = a \times \exp(bx) \qquad [1]$$

$$\textit{Spring switchgrass density} = 1/(\mathrm{a}+\mathrm{bx}) \qquad [2]$$

where a is the weed-free fall switchgrass cover (Equation 1) or the spring switchgrass density (Equation 2), and b is the rate of decline of fall switchgrass cover (Equation 1) or spring switchgrass density (Equation 2) with increasing foxtail density.

Yield Loss Model. The rectangular hyperbolic yield loss model described by Cousens (1985) was used to relate yield loss in the first production year to weed density early in the establishment year:

$$YL = (Id/1)+(Id/A) \qquad [3]$$

where YL is the percentage yield loss relative to a weed free control, d is the weed density, I is a model parameter representing the percentage of yield loss per unit of weed density as $d \rightarrow 0$, and A is a model parameter representing the percentage yield loss as $d \rightarrow \infty$. Yield loss was calculated by subtracting the yield from the average weed-free yield, dividing by the weed-free yield, and multiplying by 100. There was no block effect at any site–year, so the weed-free yield was averaged across blocks for each site–year. Foxtail density was measured in 2-wk intervals after switchgrass emergence through August, and the measurement timing was associated with the peak foxtail density used in all analyses.

To determine whether data could be pooled across site–years, we followed the extra sum of squares procedure described by Lindquist et al. (1996), which tests whether parameters and models vary among site–years. If models and parameters did not differ among site–years, they were combined for analysis.

The statistical software R version 2.11.1 (R Development Core Team, 2010) was used to perform all analyses. The regressions and yield loss models were fit using R package *nlme* (Linear and Nonlinear Mixed Effects Models, R package version 3.1-97, 2010).

Results and Discussion

Temperature and precipitation patterns during the 2011 and 2012 growing seasons were atypical (Table 1). In 2011, average air temperatures were 12% higher in July, but 9 to 11% cooler in September compared with 30-yr averages. In 2012, a warm spring and early summer resulted in temperatures 21, 12, and 17% above average in May, June, and July, respectively, at the Janesville site. Precipitation was below average throughout the growing season as all site–years received between 43 and 70% of the 30-yr average rainfall in the growing season of the establishment year. Drought conditions were particularly severe in June 2012 at the Janesville

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Table 1. Precipitation by month for Arlington and Janesville from May to October of the establishment year; 30-yr averages are based on the period from 1981 to 2010.

Month	Arlington, WI		Janesville, WI		
	30-yr average	2011	30-yr average	2011	2012
	cm				
May	7.3	6.2	9.6	3.6	6.1
June	11.9	8.9	11.1	3.4	0.8
July	10.5	5.4	8.6	6.4	8.9
August	9.9	3.8	11.4	2.7	6.5
September	9.0	10.2	8.4	6.0	5.4
October	6.5	4.1	7.4	2.2	4.1
Total	55.1	38.6	56.5	24.3	31.8

site because this location received 7% of the 30-yr average precipitation for that month.

Foxtail densities peaked at four wk after switchgrass emergence and then declined through August (data not shown). Therefore, total foxtail density at four wk after switchgrass emergence was used to represent early season weed density in all analyses. At that timing, foxtail density ranged from 0 to 73, 109, and 96 plants m^{-2} at Arlington, Janesville 2011, and Janesville 2012 sites, respectively. Annual grass cover in the establishment year varied by treatment but was consistently dominated by giant foxtail, which reached 72, 79, and 52% cover in September at Arlington, Janesville 2011, and Janesville 2012 sites, respectively. Although yellow foxtail was seeded in equal proportions as giant foxtail, cover in September of the establishment year was 8% or less in any site–year (data not shown).

Switchgrass Establishment. The relationship between early season foxtail density and the cover of switchgrass in fall of the establishment year was different at each site–year ($P \leq 0.01$), so site–years were analyzed separately (Figure 1A). Both parameters of the concave exponential function (*a*, weed-free switchgrass cover; *b*, rate of decline with increasing foxtail density) differed among site–years ($P < 0.05$). Regression analysis found 1 foxtail plant m^{-2} was associated with a reduction in the percentage of fall switchgrass cover of 14, 22, and 27% at Arlington, Janesville 2011, and Janesville 2012 site–years, respectively. As total foxtail density increased from 0 to 10 plants m^{-2}, fall switchgrass cover decreased 73, 52, and 37% at Arlington, Janesville 2011, and Janesville 2012 site–years. This corresponds to a 78 to 96%, reduction from the weed-free cover. At foxtail densities of 20 plants m^{-2}, switchgrass fall cover was reduced below 4% across all site–years. Our results suggest fall cover to be a useful measure for assessing establishment success. Although no published threshold of establishment success based on fall cover exists, to our knowledge, other experiments we have conducted agree with this observation (Renz et al. 2012). Others have developed thresholds based on spring frequency of switchgrass 1 yr after planting, but this relationship has not, to our knowledge, been evaluated in the fall of the establishment year (Schmer et al. 2006).

Ten to 20 switchgrass plants m^{-2} by spring of the first production year is considered the threshold for successful establishment (Launchbauch and Owensby 1970), with 20 plants m^{-2} considered fully successful and productive in the first harvest, and 10 plants m^{-2} considered low, but capable of reaching full productivity (Vogel and Masters 2001). Spring switchgrass density did not differ in its relationship to foxtail density at Janesville in 2011 and 2012 ($P = 0.64$), thus these site–years were combined for analysis. The site–year established at Arlington differed from both Janesville sites ($P < 0.0001$) and was analyzed separately (Figure 1B). At the Janesville site, a foxtail density of > four plants m^{-2} was associated with a switchgrass density < 10 plant m^{-2} threshold for establishment success, indicating failed establishment. No treatments reached the 20 plant m^{-2} threshold. At the Arlington site, > 75 foxtail plants m^{-2} were associated with spring switchgrass densities < 10 plant m^{-2} threshold, and > 29 foxtail plants m^{-2} reduced spring switchgrass density < 20 plants m^{-2}. Using the establishment index developed by Launchbauch and Owensby (1970), these results suggest that, at the Arlington site, the presence of ≤ 29 foxtail plants m^{-2} in the establishment year would not result in a yield loss in the first harvest. In contrast, ≤ 4 foxtail plants m^{-2} at the Janesville site would reduce yield in the first production year but potentially not in future harvests.

These results are consistent with other research documenting an inverse relationship between weed and switchgrass density. Kering et al. (2013) found up to a 22-fold increase in switchgrass stand development 120 d after planting switchgrass when using herbicides to suppress grass weeds. Similarly, Mitchell et al. (2010) observed that over three site–yr and two cultivars, the site–years with the highest percentage of weed frequency coincided with the site–year with the lowest percentage of frequency for switchgrass in the spring of the production year. Although they did not directly measure switchgrass density, frequency was used as a measure of establishment success and is considered an estimate of plant density (Vogel and Masters 2001).

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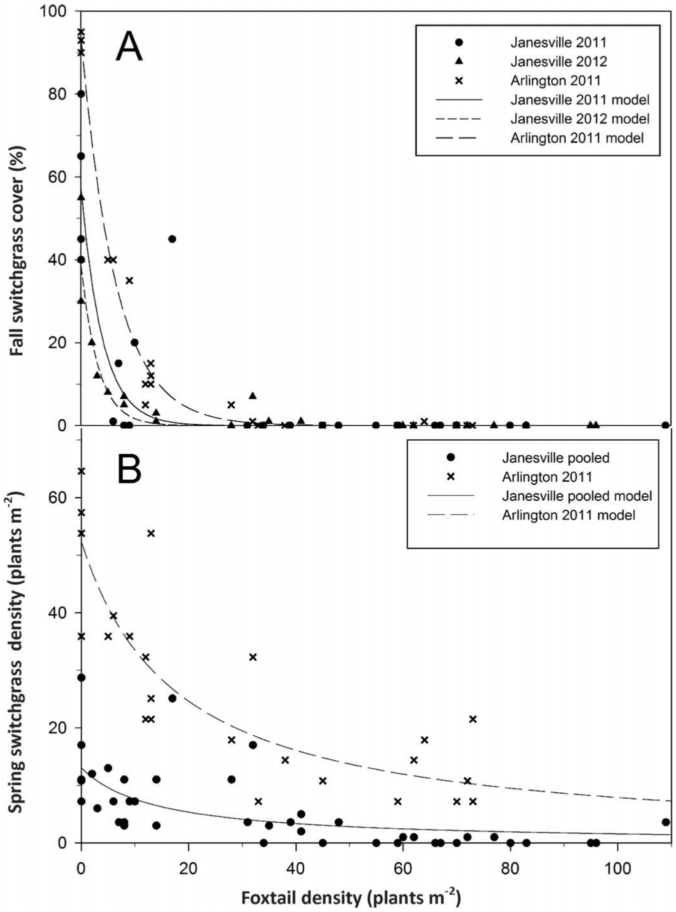

Figure 1. Effect of yellow and giant foxtail plant density 4 wk after switchgrass emergence in the establishment year on (A) switchgrass cover in fall of the establishment year, and (B) switchgrass plant density in spring of the first production year (the second growing season). The relationship between fall switchgrass cover and foxtail density (A) differed among site–years ($P \leq 0.01$); therefore, each site–year was analyzed separately ($n = 24$ for each site–year). The relationship between spring switchgrass density and foxtail density (B) did not differ between Janesville site–years ($P = 0.64$) but did differ between Janesville and Arlington site–years ($P < 0.0001$). Hence, data from Janesville site–years were pooled ($n = 42$) for analysis but were analyzed separately from the Arlington site data ($n = 24$). (A) root mean square error $(RMSE)_{Arl11} = 2.19$, $RMSE_{Jan11} = 3.54$, $RMSE_{Jan12} = 1.95$, all on 22 df. (B) $RMSE_{Arl11} = 3.00$ on 22df, $RMSE_{Jan\text{-}pooled} = 2.24$ on 46 df.

Additional factors besides foxtail density likely affected spring switchgrass density. At the Arlington site, high switchgrass emergence resulted in high plant density throughout the establishment year ($>$ 100 plants m^{-2} in weed-free controls), whereas, at the Janesville site, emergence was fivefold less ($<$ 20 plants m^{-2} in the weed-free control). Elevated switchgrass density at the Arlington site allowed for a greater loss of switchgrass plants before the threshold (20 plants m^{-2}) was reached, and the higher seedling density likely provided additional weed suppression. Increased weed suppression from increased seedling density has been observed by others in switchgrass establishment (Curran et al. 2012).

Switchgrass Yield Loss. Model parameters did not differ among site–years ($P \geqslant 0.36$); consequently, data from site–years were pooled for analysis of yield loss. The rectangular, hyperbolic, yield loss model described by Cousens (1985) fit the relationship between foxtail plant density at four wk after switchgrass emergence and switchgrass biomass yield (Figure 2; Table 2). Weed-free switchgrass yields ranged from 4.90 to 19.08 Mg ha^{-1}, with an average ($\pm$ SE) of 10.96 $\pm$ 0.77 Mg ha^{-1} across 3 site–yr (Table 2). The *I* parameter (initial slope) indicates switchgrass was very sensitive to foxtail competition because yields were reduced by 25% for each foxtail plant per square meter as foxtail density approaches zero. Maximum yield loss, as determined by the model ($A = 100\%$), was observed at maximum foxtail densities (Table 2). The low root mean square error (3.684) and stability of *I* and *A* among site–years indicates that foxtail competition during switchgrass establishment results in a consistent yield–loss response, making this model useful for weed management decisions. Relative annual grass cover and biomass in the production year were also collected but were found to be highly correlated ($P < 0.001$) with foxtail weed density in the establishment year (data not shown). This supports our belief that foxtail density in the establishment year was the driving factor in observed switchgrass yield in the first production year.

Although yield loss models have not been previously examined, to our knowledge, other researchers have observed yield loss from annual grass competition. Miesel et al. (2012) found switchgrass yield in the first production year to be correlated with annual grass abundance in the establishment year, with a 10% increase in grass weed abundance resulting in a 32% yield reduction. Similar yield losses have also been observed with other warm season (C_4) grass crops. Wang et al. (2010) found that an increase of 1 green foxtail [*Setaria viridis* (L.) Beauv.] plant m^{-2} reduced foxtail millet [*Setaria italica* (L.) Beauv.] yields 29% at low foxtail densities. Similar yield losses were found by Tamado et al. (2002) in sorghum [*Sorghum bicolor* (L.) Moench. ssp. *drummondii* (Nees ex Steud.) de Wet & Harlan] competing with ragweed parthenium (*Parthenium hysterophorus* L.).

We hypothesize that the high level of competition is due to the earlier emergence and faster growth rates of giant foxtail, the dominant weed in this

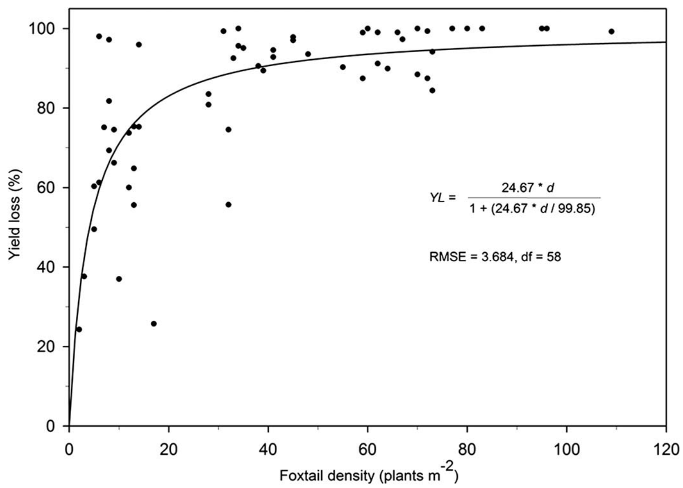

Figure 2. Effect of yellow and giant foxtail combined plant density (d) at 4 wk after switchgrass emergence on switchgrass biomass yield loss (YL) in the first production year (second growing season). Switchgrass biomass yield loss was calculated relative to a weed-free biomass yield. No differences existed between yield loss models among site–years ($P > 0.36$), consequently data were pooled ($N = 60$).

study, as compared with switchgrass (Leon et al. 2004; Patterson 1985). Conley et al. (2002) found earlier-emerging cohorts of giant foxtail to be more competitive with soybean [*Glycine max* (L.) Merr.] than later-emerging cohorts. Moechnig et al. (2003) and Knezevic and Horak (1998) have also recognized the importance of relative weed emergence timing on crop and weed development and resulting yields.

The stability of the I coefficient among three site–yr indicates that foxtails consistently reduced switchgrass yields at low densities. This was not expected because previous research (Curran et al. 2012; Miesel et al. 2012; Renz 2011) has found variable effects of annual grass competition in the establishment year

Table 2. Mean weed-free switchgrass yields (± SE) and estimated model parameters (I and A) of the rectangular hyperbolic model $YL = I \times (d/1) + [I \times (d/A)]$ for switchgrass yield loss as a function of yellow and giant foxtail weed density (plants per square meter) at 4 wk after switchgrass emergence. Model parameters did not differ among site–years ($P \geqslant 0.36$); consequently, data from all site–years were pooled for analysis of yield loss ($n = 60$).

	Model parameters[a]		
Weed-free yield ± SE	I ± SE	A ± SE	RMSE[b]
Mg ha^{-1}	%	%	%
10.96 ± 0.77	24.67 ± 4.25	99.85 ± 3.16	3.684

[a] I is the percent yield loss as weed density approaches zero; A is the yield loss as the weed density approaches infinity. Both parameters differed from zero ($P < 0.0001$).
[b] Abbreviation: RMSE, root mean square error.

on switchgrass yield. Differences could be due to relative emergence timing of switchgrass and annual grass species in this study compared with others. Research has shown this to be an important factor in switchgrass establishment (Hsu et al. 1985; Vogel 2004) as well as the establishment of other crops when competing with giant foxtail (Conley et al. 2002; Moechnig et al. 2003). Another potential explanation is that the competitive ability of annual grass weeds in other studies was reduced compared with this study. Herbicides were used in studies by Curran et al. (2012), Miesel et al. (2012), and Renz (2011), and it has been documented that herbicide treatments can reduce the competitive ability of annual grasses even if targeting broadleaf weeds (Rinella et al. 2010a,b). In addition, it is a common practice to mow fields in mid to late summer as an additional weed management method in the establishment year (e.g., Casler and Boe 2003; Miesel et al. 2012). Although we did not evaluate this management method, it was used in other studies that have documented limited effects from annual grasses (e.g., Curran et al. 2012). It is plausible that mowing reduces the competitive effects of annual grass weeds and allows for improved switchgrass establishment and productivity the following year.

Our results suggest that, for switchgrass to establish successfully, foxtail control may be required, depending on foxtail density and site-specific parameters. Two of the three site–yr required control of foxtail populations when densities exceeded four plants m^{-2} to maintain acceptable switchgrass stand density the following spring. If productivity is to be maximized in the first production year, all early emerging foxtails should be controlled because just 1 foxtail plant m^{-2} reduced yields in the first harvest by 25%. Although yield-loss is substantial in the first production year, some evidence suggests that this reduction will diminish in subsequent harvests as stands reach full productivity (Renz 2011; Schmer et al. 2006; Vogel and Masters 2001). Future research should evaluate the long-term effects of annual grass weed competition on yield loss in the second production year and beyond.

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