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Abstract Weed interference limits switchgrass (*Panicum virgatum* L.) establishment from seed. Our objectives were to determine the effect of selected post-plant, preemergence herbicides on stand establishment and subsequent biomass yields of adapted upland switchgrass cultivars grown in three environments in the Central and Northern Great Plains. A separate experiment was conducted in eastern Nebraska to determine if there were any differences among switchgrass ecotypes for herbicide tolerance to the optimal herbicide combination. Herbicides applied immediately after planting were different concentrations of atrazine [Aatrex 4L®; 6-chloro-*N*-ethyl-*N*′-(1-methylethyl)-1,3,5-triazine-2,4-diamine], quinclorac (Paramount®; 3,7-Dichloro-8-quinolinecarboxylic acid), atrazine+quinclorac, imazapic {Plateau®; 2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-methyl-3-pyridinecarboxylic acid}, and quinclorac+imazapic. Herbicide efficacy was determined by measuring stand frequency of occurrence and biomass yield the year after establishment. The application of quinclorac plus atrazine resulted in acceptable stands and high biomass yields. Imazapic often reduced switchgrass stands in comparison to the nontreated control and is not recommended for switchgrass establishment. In the multi-state trials, the herbicide by cultivar interaction was not significant for stands or biomass yields, indicating that the effects of herbicides on switchgrass stands and biomass yields were consistent over the upland cultivars used in the trials. No differences were detected among switchgrass lowland and upland ecotypes for tolerance to atrazine and quinclorac. Quinclorac, which provides effective control of grassy weeds, and herbicides such as atrazine which provide good broadleaf weed control are an excellent herbicide combination for establishing switchgrass for biomass production in the Great Plains and the Midwest.

Keywords Bioenergy · Dedicated energy crops · Switchgrass · Weed control

Abbreviations

a.i. active ingredient
PLS pure live seed

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Introduction

Switchgrass (*Panicum virgatum* L.) has been identified as an important perennial crop for biomass energy and is a productive warm-season pasture grass for temperate grasslands. This native, warm-season tallgrass is broadly adapted to most of North America except for the areas west of the Rocky Mountains and north of 55° N lat. [12]. It has excellent biomass production potential [14] throughout a broad geographic range and has desirable conservation attributes including carbon sequestration [3, 8]. Switchgrass has two distinct ecotypes, lowland and upland [12]. Lowland ecotypes are found on flood plains and other areas that receive run-on water, whereas upland ecotypes occur in upland areas that are not subject to inundation.

Weed competition is a major reason for switchgrass stand failure [6, 10, 12]. The successful establishment and harvestable yield of a switchgrass stand can be delayed by one or more years because of competition from weeds [10]. Failure to obtain a fully successful switchgrass stand during the year of planting can limit biomass yield in post-establishment years resulting in decreased revenue [7]. Herbicidal control of weeds significantly improves establishment success [12].

Most dicot weeds can be controlled in switchgrass with 2,4-D (2,4-dichlorophenoxyacteic acid) [12]. Atrazine has improved switchgrass establishment by controlling broadleaf weeds and C_3 (cool season) weedy grasses [1, 5], but it has limited effectiveness for controlling warm-season annual grasses such as foxtails (*Setaria* spp.). Previous unpublished herbicide screening research by USDA-ARS in Lincoln, NE indicated that switchgrass establishment was improved by imazapic (Plateau®) application at 35 g a.i. ha^{-1} or atrazine (Aatrex 4L®) at 2.2 kg a.i. ha^{-1} + quinclorac (Paramount®) at 280 g a.i. ha^{-1}.

A primary objective of this study was to determine the effect of promising preemergence herbicides and herbicide combinations identified in previous screening research on switchgrass stand establishment and subsequent biomass yields in the Central and Northern Great Plains, USA. Because of anecdotal reports that lowland switchgrass lacked tolerance to quinclorac, an additional experiment was completed to determine if there were differences among switchgrass ecotypes for tolerance to quinclorac which may inhibit lowland ecotype establishment.

Materials and Methods

Field experiments were conducted near Mead, Nebraska (NE), Highmore, South Dakota (SD), and Mandan, North Dakota (ND) to assess the influence of selected herbicides on switchgrass cultivar establishment across a range of environments. Switchgrass cultivars were planted at 330 pure live seeds m^{-2} in 8×5-m plots on 16, 24, and 25 May, 2000, at NE, SD, and ND, respectively. “Cave-In-Rock” and “Trailblazer” were planted at all locations. Additionally, “Sunburst” was planted at SD, and “Forestburg” was planted at ND. Switchgrass plots were planted with a plot drill (Hege Inc., Waldenburg, Germany) into a clean, firm seedbed that was disked, harrowed, and cultipacked within 14 days prior to planting. The experimental design at all locations was a randomized complete block with a split-plot arrangement of treatments. Herbicide treatments were randomized as main plots and cultivars as subplots.

Herbicide treatments applied immediately after planting were as follows: A1 = atrazine at 1.1 kg a.i. ha^{-1}; A2 = atrazine at 2.2 kg a.i. ha^{-1}; Q1 = quinclorac at 280 g ha^{-1}; Q2 = quinclorac at 560 g ha^{-1}; I1 = imazapic at 35 g ha^{-1}; and the combinations A1Q1 (A1 + Q1), A1Q2 (A1 + Q2), and I1Q1 (I1 + Q1). At NE, an additional treatment, I1Q2 (I1 + Q2) was included. Nontreated control plots were included in the herbicide treatments. Herbicide spray solutions were applied with a tractor-mounted sprayer to deliver 190 L ha^{-1}. There were four replicates per treatment combination. No additional treatments were applied to plots during the establishment year.

Residue was removed from plots prior to switchgrass emergence in spring 2001 by burning at ND and by mowing and raking at NE. At SD, residue was shredded with a rotary mower since biomass was insufficient to warrant burning or removal by mowing and raking due to drought conditions during the 2000 growing season. Evaluating stands in spring 2001 rather than in autumn 2000 allowed stands to over-winter which accounted for winter kill and provided a better representation of the plants that established as a result of herbicides applied immediately after planting.

The effectiveness of the herbicides in improving switchgrass establishment was determined by measuring stand frequency of occurrence and herbage dry matter yield. In late May or early June 2001, switchgrass and weed frequency were measured using a frequency grid [13]. Prior to harvest in late autumn after a killing frost, the length of each plot at each location was trimmed to 3 m. The percentage of the total biomass that was weeds in each plot was estimated visually by two independent observers before harvest. Switchgrass biomass yield was determined by cutting and weighing a 0.9-m wide × 3-m long swath from each subplot using a flail-type plot harvester with a cutting height of 10 cm. The outer rows of the subplots were not harvested for yield to reduce border effects. Four plots of each cultivar at each location were subsampled to determine dry matter concentration of the biomass for each cultivar. Mean dry matter concentration of the subsamples was used to adjust biomass yields to oven dry weights. The data were analyzed separately for each location using PROC MIXED in SAS [4] and as a split-plot design with herbicide treatments as the whole plot and switchgrass cultivars as the subplot using PROC GLM in SAS [9].

Herbicides and cultivars were considered fixed effects. The analyses yielded the same results, so probability values are presented from the GLM procedure with appropriate mean squares which show the relative magnitude of the sources of variation. The frequency data (%) for stands and weeds were arc-sine transformed for analysis. Results for arc-sine transformed data were similar to those for nontransformed percentages so nontransformed treatment means are reported.

An additional experiment was established at Mead, NE in 2002 to test if lowland and upland ecotypes differed in tolerance to preemergence applications of quinclorac and atrazine at the optimal rate determined by the previous multi-state research. The lowland entries in this study were "Kanlow," "Alamo," an experimental strain Sco-99-TNC, and two lowland x upland experimental hybrid strains. The upland entries in the test were "Shawnee," Trailblazer, "Summer," "Blackwell," Sunburst, and a Nebraska experimental strain. The small plot procedures were the same as those described previously for the multi-state experiment, except plot size was 3.0×1.2 m. Seeding rate was 400 PLS m^{-2}. Plots were planted on 6 June, 2002 in a randomized complete block field design with six replicates. A preemergence application of a tank mixture of quinclorac at 560 g ha^{-1} and atrazine at 1.1 kg a.i. ha^{-1} was applied on 12 June, 2002. The tank mix included a surfactant (methylated seed oil) at 1.75 l ha^{-1}. The number of emerged seedlings per meter of row and stand frequencies were measured on 14 and 16 July, 2002. No harvests were made on the establishment year. The plots were burned on 1 April, 2003. The post-establishment year procedures were the same as described for the multi-state experiment except plots were fertilized with 112 kg N ha^{-1} on 23 April, 2003. The data were analyzed using PROC MIXED and GLM in SAS to test for differences among ecotypes and strains within ecotypes for tolerance to the herbicide treatment combination. Ecotypes and strains were considered fixed effects. Data were handled as previously described.

Results and Discussion

The three multi-state experiments were visually evaluated in August 2000. Herbicide effectiveness and switchgrass establishment appeared to be adversely affected by drought conditions that occurred at Highmore, SD during June and July 2000 (Fig. 1). Precipitation at Highmore in 2000 was 21% below the long-term mean in June and 52% below the long-term mean in July. At Mead, NE, broadleaf weeds dominated: primarily velvetleaf (*Abutilon theophrasti* Medik.), common waterhemp (*Amaranthus rudis* Sauer), and annual sunflower (*Helianthus annuus* L.). At Mandan, ND, the dominant weeds were annual grasses; primarily stinkgrass [*Eragrostis cilianensis* (All.) Vignolo ex Janch.] and foxtails (*Setaria* spp.). Regardless of herbicides, SD had reduced switchgrass frequency compared to the other sites.

In the year after establishment (2001), there were significant differences in switchgrass stands due to herbicide treatments at NE and ND (Tables 1 and 2). Imazapic or treatments containing imazapic significantly reduced switchgrass stands in ND compared to other herbicide treatments, including the nontreated control. Similar results were obtained in NE, except the herbicide treatment differences were not always significant. At SD, the dry conditions adversely affected switchgrass stands, and no differences between treatments were observed. Imazapic is not recommended for establishing pure switchgrass stands [2]. The other herbicide treatments did not have an adverse effect on stands at any of the locations.

In the Great Plains, stands with switchgrass frequencies of 50% or higher can be classified as fully successful, switchgrass frequencies of 25% to 50% indicate adequate stands, and switchgrass frequencies of less than 25% are regarded as marginal or unacceptable and may require re-establishment [13]. The stands at SD were marginal due to low rainfall during June and July the previous growing season (Table 2, Fig. 1). Although stands were marginal, the plots did produce harvestable biomass the year following establishment. This was likely

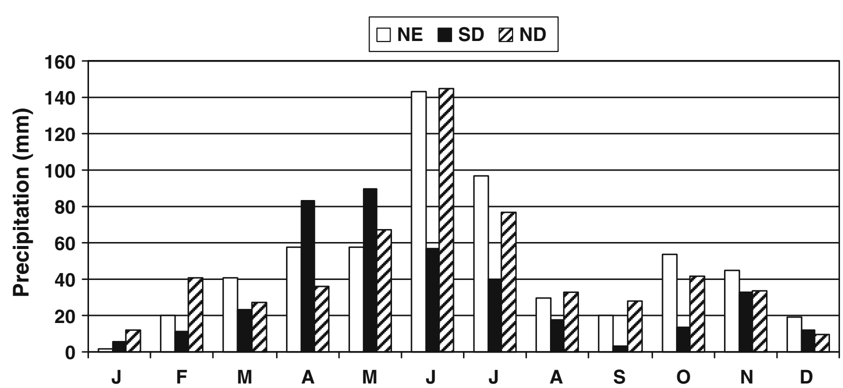

Fig. 1 Monthly precipitation in 2000 at Mead, NE, Highmore, SD, and Mandan, ND. Total annual precipitation in 2000 was 587, 391, and 551 mm at Mead, Highmore, and Mandan, respectively

Table 1 Analysis of variance of switchgrass biomass yields, switchgrass frequency, and weed frequency the year after establishment (2001) in response to post-plant preemergence herbicide applications the year of establishment (2000) in the Central and Northern Great Plains

Source of variation	*df*	Mean squares		
		Yield (Mg ha^{-1})	Switchgrass frequency arc sine (%/100)	Weed frequency
Nebraska				
Replicates	3	9.60	0.112	0.502
Herbicides	9	15.17**	0.195*	0.106*
Error a	27	4.24	0.081	0.044
Cultivar	1	14.37**	0.758**	1.188**
Cultivar x herbicide	9	2.20	0.020	0.108*
Error b	68	1.57	0.041	0.049
South Dakota				
Replicates	3	5.10	0.022	0.243
Herbicides	8	8.30	0.027	0.701**
Error a	24	7.05	0.022	0.091
Cultivar	2	14.26**	0.045**	0.124*
Cultivar x herbicide	16	1.54	0.004	0.059
Error b	54	1.15	0.006	0.033
North Dakota				
Replicates	3	0.75	0.086	0.052
Herbicides	8	8.98	0.955**	0.142**
Error a	24	5.22	0.069	0.044
Cultivar	2	50.86**	0.068	0.015
Cultivar x herbicide	16	1.91	0.070	0.027
Error b	54	2.20	0.042	0.021

*P=0.05,**P=0.01, indicates levels of significance

due to the herbicide treatment that was applied in the spring of 2001 which allowed the thin stands to increase in response to reduced weed competition and adequate precipitation.

There were significant differences in weed frequency and contribution to biomass at all locations due to herbicide treatments (Tables 1 and 2). This was due to the effect the herbicide had on first year stands and on weeds that were

Table 2 Switchgrass biomass yield (Mg ha^{-1}), switchgrass frequency of occurrence (%), and weed contribution to biomass (%) in 2001 following the application of post-plant preemergence herbicides and combinations at planting in 2000 at three locations in the Central and Northern Great Plains

Treatment	Biomass yield (Mg ha^{-1})			Switchgrass frequency (%)			Weed contribution to biomass (%)		
	NE	SD	ND	NE	SD	ND	NE	SD	ND
A1	4.2	3.7	5.5	81	9	67	25	60	0
A1Q1	6.4	6.2	6.2	81	20	66	7	10	1
A1Q2	7.4	5.9	5.6	77	19	66	9	4	1
A2	5.6	4.5	5.3	80	16	55	7	34	4
Q1	6.7	5.2	6.7	77	11	74	12	5	1
Q2	7.3	4.9	6.2	66	15	49	17	5	3
I1	6.1	5.0	3.7	70	19	8	2	13	28
I1Q1	7.0	5.6	5.1	60	19	20	4	12	5
I1Q2	6.4	–	–	54	–	–	4	–	–
Nontreated	3.9	4.2	5.1	72	8	73	26	46	3
LSD 0.05	0.7	NS	NS	9	NS	5	4	6	7

A1 atrazine 1.1 kg ha^{-1}, *A2* atrazine 2.2 kg ha^{-1}, *Q1* quinclorac 280 g ha^{-1}, *Q2* quinclorac 560 g ha^{-1}, *I1* imazapic 35 g ha^{-1}, *A1Q1* A1 + Q1, *A1Q2* A1 + Q2, *I1Q1* I1 + Q1, *I1Q2* I1+ Q2

Table 3 Biomass yield (Mg ha^{-1}), switchgrass frequency of occurrence (%), and weed frequency of occurrence (%) for switchgrass cultivars in 2001 following the application of post-plant preemergence herbicides and combinations at planting in 2000 at three locations in the Central and Northern Great Plains

Cultivar	Biomass yield (Mg ha^{-1})			Switchgrass frequency (%)			Weed frequency (%)		
	NE	SD	ND	NE	SD	ND	NE	SD	ND
Cave-In-Rock	6.6	5.5	5.6	80	18	56	2	15	6
Trailblazer	5.8	5.3	6.6	68	11	50	20	24	4
Sunburst	–	4.3	–	–	16	–	–	24	–
Forestburg	–	–	4.2	–	–	53	–	–	4
LSD 0.05	0.1	0.1	0.1	1	1	NS	1	1	NS

controlled in the establishment year. Herbicide treatments that targeted both grassy and broadleaf weeds the establishment year, such as quinclorac plus atrazine, tended to have lower weed frequency the year after establishment. The additive effect of combining quinclorac and atrazine was particularly evident at NE where the control of Setaria spp. and barnyardgrass (*Echinochloa crus-galli* (L.) P. Beauv.) was excellent. Nontreated plots tended to have the highest weed frequencies the year after establishment, even though a combination grass–broadleaf weed herbicide was applied the spring after establishment.

Herbicide treatments had a significant effect on biomass yields the year after seeding at NE (Table 2). The nontreated plots had significantly lower biomass yields than plots treated with herbicides. Plots treated with herbicide combinations that controlled grassy and broadleaf weeds produced more biomass than herbicides that controlled only broadleaf weeds. The plots treated with atrazine plus quinclorac produced 0.8 to 3.2 Mg ha^{-1} more switchgrass biomass than the plots that received only atrazine.

In general, there were few differences in biomass yield observed between treatments, and the relatively low switchgrass frequencies at SD resulted in surprisingly high biomass yields (Table 2). For example, when biomass yields were averaged across sites, treatments Q1 and Q2 averaged 6.2 and 6.13 Mg ha^{-1}, respectively, which were similar to A1Q1 (6.27 Mg ha^{-1}) and A1Q2 (6.3 Mg ha^{-1}). However, Q1 and Q2 did not provide consistent weed control and stand establishment across sites when compared to A1Q1 and A1Q2. The herbicide treatment of A1Q2 (atrazine 1.1 kg ha^{-1} + quinclorac 560 g ha^{-1}) resulted in fully successful stands at NE and ND and high biomass yields and low weed contribution to biomass at all three locations (Table 2). Of the treatments evaluated, A1Q2 appears to be an excellent herbicide combination for establishing switchgrass for biomass production in the Central and Northern Great Plains.

Cave-In-Rock and Trailblazer were evaluated at each location, with Sunburst added at the South Dakota site and Forestburg added at the North Dakota site. The two or three cultivars were evaluated to determine if any herbicide by cultivar interactions occurred (Table 3). These cultivars represent the diversity of cultivars available for use in the Central and Northern Great Plains. Herbicide by cultivar interactions were not significant for stands or biomass yields but were significant for weed percentages at NE (Table 1). Trailblazer plots usually had more weeds than Cave-In-Rock plots, but the differences were not consistent over herbicides. These results indicate that herbicide effects are consistent over cultivars for switchgrass biomass and stands.

There were significant cultivar main effects for switchgrass biomass at all three locations and for switchgrass stands and weeds at NE and SD (Table 3). Switchgrass biomass yield for all cultivars across all locations exceeded

Table 4 Analysis of variance mean squares for comparing upland and lowland ecotypes of switchgrass for tolerance to preemergence applications of quinclorac at Mead, NE

Source	*df*	Mean squares			
		2002 seedlings (Number m^{-1})	2002 frequency (%)	2003 frequency (%)	2003 biomass yield (Mg ha^{-1})
Ecotype	1	59	115	449	34.22**
Strain (Ecotype)	9	579**	3127**	1081**	9.20**
Replicate	5	647**	379	1057**	0.51
Error	50	189	238	129	1.50

Establishment criteria were establishment year (2002) seedling number/m of drill row 6 weeks after planting, 2002 switchgrass frequency of occurrence, post-establishment year (2003) switchgrass frequency of occurrence, and 2003 biomass yield

*P=0.05,**P=0.01, indicates levels of significance

Table 5 Establishment year (2002) seedling number/m of drill row and switchgrass frequency of occurrence, post-establishment year (2003) switchgrass frequency of occurrence, and 2003 biomass mean yields for 11 switchgrass strains planted at Mead, NE in 2002 and treated with a post-plant, preemergence application of a tank mixture of quinclorac at 560 g ha^{-1} and atrazine at 1.1 kg ha^{-1}

Strain	Ecotype	2002 seedlings (Number m^{-1})	2002 switchgrass frequency (%)	2003 switchgrass frequency (%)	2003 biomass yield (Mg ha^{-1})
Alamo	Lowland	22.7	69.7	67.3	9.8
Kanlow	Lowland	24.2	43.3	64.5	11.7
KxSHP1Syn2	Lowland	41.2	69.8	87.5	10.3
SxKHPSyn2	Lowland	17.7	51.8	70.5	10.4
Sco-99-TNC	Lowland	18.2	22.5	57.2	8.5
Lowland Mean		24.8	51.4	69.4	10.1
Blackwell	Upland	42.3	81.5	90.5	12.5
Cave-In-Rock C2	Upland	19.0	40.2	65.0	12.1
Shawnee	Upland	29.3	62.7	85.7	12.8
Summer	Upland	18.0	18.7	58.3	9.5
Sunburst	Upland	18.2	41.3	60.3	10.4
Trailblazer	Upland	33.2	80.2	88.0	12.2
Upland Mean		26.7	54.1	74.6	11.6
Probability > F		0.0062	<0.0001	<0.0001	<0.0001

The probability >*F* values tested strains within ecotypes

4 Mg ha^{-1} in the first year after establishment. Cave-In-Rock had greater biomass and stands than Trailblazer at NE, but both cultivars had excellent production and stand frequencies. At SD, all cultivars had low switchgrass frequencies due to drought conditions in 2000 (Fig. 1), but biomass yields were greater than expected given the relatively low switchgrass frequencies (Table 3). Although Cave-In-Rock appears to be more competitive at NE and SD due to its greater biomass and stand frequencies and reduced weed frequencies (Table 3), it is not possible to determine if the divergence was due to genetic differences among cultivars for establishment capability. Cave-In-Rock has more yield potential when grown in USDA Plant Hardiness Zones 5 and 6 than Forestburg and Sunburst but has less yield potential when moved north of its area of adaptation. In general, the different switchgrass cultivars performed as expected based on their area of adaptation and yield potential from previous research.

There were no significant differences among switchgrass ecotypes for seedlings per meter of row (P=0.58), establishment year switchgrass frequency (P=0.47), or post-establishment year switchgrass frequency (P=0.06) for upland and lowland ecotypes (Table 4). There were differences among strains for establishment year seedlings per meter of row (P<0.01) and switchgrass frequency (P<0.01) and post-establishment year switchgrass frequency (P<0.01) (Table 4). However, to specifically address our research objective, the mean establishment year and post-establishment year switchgrass frequencies for both ecotypes were fully successful (>50%; Table 5) using accepted standards [11, 13] and provide no evidence to suggest lowland switchgrass ecotypes lack tolerance to quinclorac. There were differences among ecotypes and strains for post-establishment year biomass yields, but yields were excellent for all ecotypes and strains (Tables 4 and 5). The upland ecotypes, which are better adapted to dry environments, averaged 1.5 Mg ha^{-1} greater biomass yields than the lowland ecotypes (Table 5), which was likely due to drought conditions that occurred in eastern Nebraska during this period (Fig. 2). Although ecotype and strain differences occurred, this experiment was designed only to determine if quinclorac inhibits lowland ecotype establishment. These results demonstrate clearly that both lowland and upland switchgrass ecotypes and strains are tolerant to preemergence applications of quinclorac and atrazine.

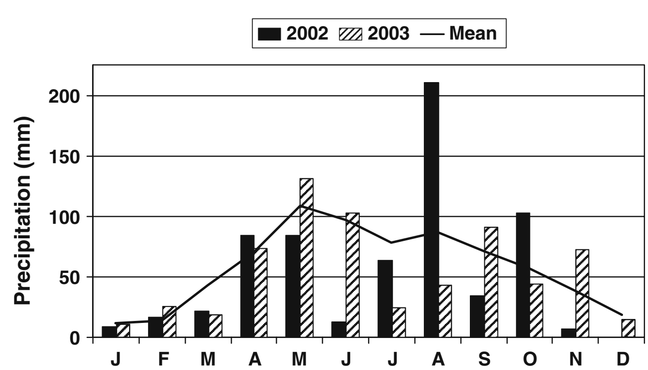

Fig. 2 Long-term average precipitation and monthly precipitation in 2002 and 2003 at Mead, NE. Total annual precipitation was 58 and 53 mm below the long-term average in 2002 and 2003, respectively

Potential Impact

The combined use of atrazine and quinclorac promoted fully successful establishment of adapted lowland and upland switchgrass strains in the Central and Northern Great Plains. Combining atrazine and quinclorac promoted switchgrass establishment without any apparent deleterious effects to cultivars or strains included in this study and enhanced biomass yields and controlled weeds the year after establishment in comparison to nontreated control plots. The switchgrass plots in the multi-state study were not fertilized the year after establishment. If switchgrass stands are adequate (25%) or fully successful (50%) as determined by using the frequency grid, a positive response to N fertilization can be expected [15]. The biomass yields obtained in the comparison of lowland and upland ecotypes (Table 5) demonstrate the yields that can be obtained in the year after seeding if weeds are controlled at planting and N fertilization is applied to switchgrass grown as a biomass energy crop even during periods of below normal precipitation.

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