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Robert B. Mitchell
USDA-ARS, rob.mitchell@ars.usda.gov

Kenneth P. Vogel
University of Nebraska-Lincoln, kvogel1@unl.edu

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Grass Invasion into Switchgrass Managed for Biomass Energy

R. B. Mitchell[1] · K. P. Vogel[1]

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Abstract Switchgrass (*Panicum virgatum*) is a C_4 perennial grass and is the model herbaceous perennial bioenergy feedstock. Although it is indigenous to North American grasslands east of the Rocky Mountains and has been planted for forage and conservation purposes for more than 75 years, there is concern that switchgrass grown as a biofuel crop could become invasive. Our objective is to report on the invasion of C_4 and C_3 grasses into the stands of two switchgrass cultivars following 10 years of management for biomass energy under different N and harvest management regimes in eastern Nebraska. Switchgrass stands were invaded by big bluestem (*Andropogon gerardii*), smooth bromegrass (*Bromus inermis*), and other grasses during the 10 years. The greatest invasion by grasses occurred in plots to which 0 N had been applied and with harvests at anthesis. In general, less grass encroachment occurred in plots receiving at least 60 kg of N ha^{-1} or in plots harvested after frost. There were differences among cultivars with Cave-in-Rock being more resistant to invasion than Trailblazer. There was no observable evidence of switchgrass from this study invading into border areas or adjacent fields after 10 years of management for biomass energy. Results indicate that switchgrass is more likely to be invaded by other grasses than to encroach into native prairies or perennial grasslands seeded on marginally productive cropland in the western Corn Belt of the USA.

K.P. Vogel retired from USDA-ARS in November 2013.

✉ R. B. Mitchell
rob.mitchell@ars.usda.gov

1 USDA Agricultural Research Service, Grain, Forage and Bioenergy Research Unit, Central-East Regional Biomass Research Center, University of Nebraska, 251 Filley Hall Food Industry Complex, Lincoln, NE 68583, USA

Keywords Big bluestem (*Andropogon gerardii*) · Bioenergy · Invasive species · Smooth bromegrass (*Bromus inermis*) · Switchgrass (*Panicum virgatum*)

Abbreviations

CRP	Conservation Reserve Program
C_3	Cool-season grasses
C_4	Warm-season grasses

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It is a concern that high-yielding, monoculture biofuel crops like switchgrass (*Panicum virgatum*) could become invasive [1]. However, based on Presidential Executive Order 13112, the term "invasive species" in the USA refers specifically to an "alien species whose introduction does or is likely to cause economic or environmental harm or harm to human health." Switchgrass is indigenous to North American grasslands east of the Rocky Mountains and south of 55° north latitude. Therefore, switchgrass does not meet the criteria for classification as an invasive species in that region since it is not an alien species. Switchgrass is a warm-season (C_4)

perennial grass that has been planted for forage and conservation purposes for more than 75 years [2] and is considered to be the model herbaceous perennial bioenergy feedstock for use on marginally productive cropland [3, 4]. More than 25 years of bioenergy research has demonstrated that switchgrass is productive and sustainable in the Great Plains and Midwest as a bioenergy or forage crop [4–6].

Although some plant species native to North America like eastern redcedar (*Juniperus virginiana*), giant ragweed (*Ambrosia trifida*), and common sunflower (*Helianthus annuus*) appear to have become more weedy over time [7], little field-based evidence supports this claim for switchgrass. Concerns over the potential for switchgrass to escape cultivation resulted in its inclusion on the California Department of Food and Agriculture's Noxious Weed List for a short time [8]. Additionally, the possibility for biofuel feedstocks like switchgrass to encroach into grassland, forest, and riparian ecosystems has prompted the Council for Agricultural Science and Technology (CAST) [9] and the Weed Science Society of America [10] to publish white papers warning of the invasive potential of herbaceous perennial feedstocks. Internationally, the Global Invasive Species Programme (GISP) included switchgrass in a list of species being used or considered for biofuel production and indicated switchgrass was invasive in the Hawaiian Islands, but included no reference for this claim [11]. Despite this concern for switchgrass, there is only one documented report of switchgrass escaping from cultivation in Orange County, CA [12], and no known records of an escape from cultivation causing economic or environmental harm or harm to human health [13], a requirement of Executive Order 13112.

Although switchgrass has been studied and planted for pasture and conservation since 1936 [2] and is considered a model bioenergy species [3], there is limited scientific information to support these invasive claims. Casler et al. [14] used molecular genetics to conclude that switchgrass cultivars are highly representative of natural germplasm in remnant prairies, indicating the evolution of an invasive genetic variant is unlikely. However, Barney and DiTomaso [15] noted that switchgrass shares many characteristics with Johnsongrass (*Sorghum halepense*), a prominent noxious weed in nearly 20 states. Using a standard weed risk assessment protocol, Barney and DiTomaso [15] concluded that switchgrass should not be cultivated as a bioenergy crop in California unless sterile cultivars are used. Conversely, it is important to note that switchgrass has been planted on millions of hectares of Conservation Reserve Program (CRP) grasslands in the USA since 1985 with no apparent invasive activity. Additionally, no records were found by Parrish and Fike [16] of cultivated switchgrass escaping from cultivation in Europe, Australia, or the Pacific Northwest. Contrary to the claims that switchgrass has the characteristics of a highly invasive species, our observations since 1985 have been that switchgrass fields in the Great Plains and Midwest typically are invaded by other perennial grasses such as big bluestem (*Andropogon gerardii*), smooth bromegrass (*Bromus inermis*), intermediate wheatgrass (*Thinopyrum intermedium*), Kentucky bluegrass (*Poa pratensis*), and other bluegrasses (*Poa* spp.). Herein, we report on the long-term persistence and competitive ability of switchgrass under different N rate and harvest date treatments after 10 years of management as a biomass energy crop on a site marginally productive for row crops. We utilized a long-term switchgrass and maize (*Zea mays*) carbon sequestration study [17, 18] whose experimental design enabled us to quantify the encroachment of North American native C_4 perennial grasses big bluestem and indiangrass (*Sorghastrum nutans*), and exotic C_3 perennial grasses smooth bromegrass and intermediate wheatgrass into established switchgrass stands managed as a biomass energy crop.

Materials and Methods

The field site is located on the University of Nebraska Agricultural Research and Development Center (ARDC) near Ithaca, NE, USA (latitude 41.151, longitude 96.401). The marginally productive cropland field has Yutan silty clay loam (fine-silty, mixed, superactive, mesic Mollic Hapludalf) and Tomek silt loam (fine, smectitic, mesic Pachic Argiudoll) soils. The field is marginally productive due to slope and a buried sand subsoil resulting in excessive drainage. It is one of the least productive fields on the ARDC, qualified for CRP at the initiation of the study, and is similar to the marginally productive fields expected to be used for switchgrass biomass production in the western Corn Belt. The carbon sequestration, biomass, and energy yields from this combined maize and switchgrass study have been reported previously [17, 18]. The experiment design, the treatments applied, and the protocols used to measure the invasion of switchgrass by other grasses are summarized as follows.

Experiment Design

The study was a randomized complete block design with split-split plot treatments replicated three times. Switchgrass main plot treatments were two cultivars of upland ecotype switchgrass, "Trailblazer" and "Cave-in-Rock," planted in 1998 and were 0.3 ha which enabled the use of commercial farm equipment. Split-plot treatments were three nitrogen (N) fertilizer levels and split-split plots were two harvest treatments. Annual N fertilizer rates were randomly assigned to the split-plots within switchgrass main plots. No fertilizer was applied during the switchgrass establishment year. In 2000, N fertilizer treatments of 0, 60, and 120 kg N ha^{-1} were initiated. Ammonium nitrate fertilizer was broadcast once annually in April with a bulk drop spreader throughout the duration of the study.

The switchgrass split-plots were split lengthwise into 9-m-wide split-split plots for harvest date treatments. Switchgrass harvest treatments consisted of a one-cut harvest either at anthesis (early August) or after a killing frost.

Switchgrass Management

Switchgrass plots were seeded directly into soybean (*Glycine max*) stubble in 1998 using a no-till drill with a planting rate of 6.7 kg ha^{-1} on a pure live seed basis. A preemergence application of 2 kg ha^{-1} atrazine [Aatrex 4 L®; 6-chloro-N-ethyl-N′-(1-methylethyl)-1,3,5-triazine-2,4-diamine] was applied for weed control and no other management inputs were applied in the establishment year. Immediately prior to switchgrass seeding, two drill rows of "Pawnee" big bluestem were seeded to separate and delineate the split-split plots. Excellent stands were obtained for all seeded grasses with virtually no gaps in the seeded rows which were spaced 15 cm apart. The 60 and 120 kg N ha^{-1} rates represent the low to high N rates recommended for switchgrass grown for bioenergy in the region [5] with the 0 N rate representative of a no-input system. Beginning in 2001, harvest treatments were applied to the split-split plots within switchgrass cultivar and N-fertility subplots. One harvest treatment was an August harvest near switchgrass anthesis and the other was after a killing frost in October or November. Plots were harvested only once each year to a 10-cm stubble height. The switchgrass biomass yield data was reported previously [17]. The big bluestem border rows were not harvested for biomass yield but were harvested and removed with the biomass on the same dates as the switchgrass harvests. Both cultivars of switchgrass and the big bluestem rows produced seed in all the post-frost harvested plots.

Occurrence of Grass Species

The study had 15-m-wide borders on the ends of the main plots and the alleys separating the fertilizer subplots which were mowed periodically during each growing season to keep the grasses in those areas from producing seed. At the time the experiment was established, the alleys were seeded to the same cultivars of switchgrass as were seeded in the plots. There were both space-planted and sward breeding and evaluation nurseries of multiple genotypes of big bluestem, indiangrass, smooth bromegrass, and intermediate wheatgrass within a 1-km radius of the study which were periodically allowed to set seed. Field and roadway borders at the experiment station had mixed stands of smooth bromegrass, tall fescue, and Kentucky bluegrass. In some years, these borders produced seed before they were mowed.

Although initially the seeded plots had virtually 100 % stands of the seeded switchgrass, by the latter half of the decade, it was visually apparent that switchgrass plots had been invaded by other grasses. The occurrence of other grass species in the switchgrass plots was determined by measuring the density of mature plants per 30 m^2 in each split-split plot during the growing season. The presence of mature plants of big bluestem, indiangrass, smooth bromegrass, and intermediate wheatgrass was determined by walking 1-m-wide transects through the center of each split-split plot on 13 August 2009. The number of mature plants of big bluestem, indiangrass, smooth bromegrass, and intermediate wheatgrass occurring in each 1-m wide by 30-m-long transect was recorded for each split-split plot. Consequently, the data represent mature plant density in number of mature plants per 30 m^2. No invasion of adjacent fields by switchgrass was observed during the 10 years of this study so no measurements were taken outside the plot areas.

Statistical Analyses

Data were analyzed using a generalized linear model to determine the effects of switchgrass cultivar, N rate, and harvest date treatments on the number of mature plants of C_3 and C_4 grasses invading switchgrass stands and associated switchgrass persistence using the GLIMMIX procedure of SAS [19]. Cultivar, N rate, and harvest date were considered fixed effects, and field replicate was a random effect. Treatment main effects and interactions were assessed using the LSMEANS and were significant at $P \leq 0.05$. Treatment means were separated using the Bonferroni adjusted P of ≤0.05. All values are presented as means and standard errors.

Results and Discussion

The first decade of this study included significant periods of drought. Annual precipitation during this long-term study ranged from 54.5 to 98.0 cm, with an 11-year average of 68.1 cm (Table 1). Annual precipitation was below the long-term average each year during the 7-year period from 2000 to 2006, ranging from 7.9 to 22.1 cm below the 30-year average (Table 1). This extended dry period prevented switchgrass from reaching its yield potential on the site.

Big bluestem, indiangrass, prairie threeawn (*Aristida oligantha*), smooth bromegrass, intermediate wheatgrass, and bluegrasses were all present in switchgrass stands within the treatment areas. However, only big bluestem, smooth bromegrass, and intermediate wheatgrass were recorded in the transects in adequate densities to analyze. The sampling methodology and timing prevented the accurate quantification of smaller-statured grasses such as the bluegrasses, which occurred in every plot, and prairie threeawn, which occurred in disturbed sites. Consequently, the encroaching plant data are presented in two categories, big bluestem, and smooth bromegrass and intermediate wheatgrass.

Table 1 Monthly and annual precipitation for 1999 through 2009 and long-term averages at the University of Nebraska Agricultural Research and Development Center near Ithaca, NE

	Month												
Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
	Precipitation (cm)												
1999	0.93	3.17	3.51	14.12	14.88	12.78	5.56	8.03	7.01	0.00	1.70	1.38	73.1
2000	0.00	3.79	1.68	5.11	7.04	15.21	8.81	3.37	1.55	6.48	3.85	1.84	58.7
2001	2.60	4.04	1.93	4.57	22.96	4.01	2.49	7.90	6.68	5.33	5.28	0.92	68.7
2002	1.92	1.15	2.59	6.91	7.52	2.03	3.15	16.74	3.58	9.27	0.63	0.00	55.5
2003	0.91	2.89	1.66	7.50	11.73	6.60	3.20	2.90	5.31	3.91	5.80	2.04	54.5
2004	3.35	2.99	6.72	2.87	10.01	6.78	5.92	2.54	8.92	1.80	7.76	0.73	60.4
2005	2.26	7.55	1.20	8.26	8.99	8.30	10.46	3.05	3.18	4.52	3.57	1.40	62.7
2006	0.69	0.00	0.00	9.55	2.26	2.97	7.90	14.17	13.44	1.93	0.28	6.02	59.2
2007	1.02	4.93	6.95	8.61	14.43	3.66	4.85	21.41	8.48	11.63	0.67	4.42	91.1
2008	0.37	1.16	4.97	10.14	14.25	28.73	11.00	1.42	9.60	11.46	2.72	2.22	98.0
2009	0.00	1.14	1.03	3.86	4.09	13.92	7.11	15.47	4.80	9.42	0.00	6.38	67.2
30-year ave.	1.40	1.90	5.60	7.20	10.80	10.80	8.60	9.40	9.20	6.00	3.30	2.30	76.6

Big Bluestem

Big bluestem was the primary invader into switchgrass plots, with big bluestem occurring in 32 of 36 transects. Invasion by big bluestem occurred by two mechanisms: sexual and asexual reproduction. As mentioned previously, big bluestem was seeded in two drill rows immediately before switchgrass seeding to provide a border between switchgrass split-plots. At seeding, these big bluestem drill rows occupied only a 15-cm strip between subplots. By the time of field sampling 12 years after seeding, the two big bluestem drill rows originally separated by 15 cm had grown together and displaced adjacent switchgrass and expanded to 1 m (Fig. 1). This vegetative encroachment occurred in both the harvested plots and the mowed alleys. In the rest of the switchgrass plot area, big bluestem invasion occurred from seed. Big bluestem appeared to be randomly distributed within each plot.

The interactions of switchgrass cultivar × N rate, cultivar × harvest date, and N rate × harvest date were significant ($P<0.01$) for the encroachment by big bluestem into the switchgrass plots as measured by big bluestem density. Evaluating the treatment main effects of cultivar ($P<0.01$), N rate ($P<0.01$), and harvest date ($P<0.01$) helps explain the patterns of big bluestem encroachment and gives insight into management implications. Averaged across N rates and harvest dates, big bluestem encroachment into Cave-in-Rock and Trailblazer averaged 0.13 and 0.49 plants m^{-2}, respectively, nearly four times greater in Trailblazer plots than in Cave-in-Rock plots. The reason for this difference between cultivars is difficult to determine, but big bluestem encroachment does not appear to be related to a difference in yield between the cultivars. When averaged over years, N treatments, and harvest dates, Trailblazer DM yield was about 8 % greater than Cave-in-Rock DM yields from 2000 to 2007. These cultivar differences are not surprising given the multiple years of below average precipitation. Trailblazer originated in a more arid environment (Nebraska) than Cave-in-Rock (southern Illinois), which may explain the greater yields for Trailblazer during this extended dry period. There may be slight differences in canopy architecture and in the competitive ability of the cultivars. Previous research at this location reported Trailblazer had a 7 % lower plant density than Cave-in-Rock in mature swards [20], which may provide more open space for the establishment of encroaching plants into Trailblazer. Additionally, Trailblazer has been reported to have about a 17 %

Fig. 1 Photograph of the two big bluestem drill rows 10 years after seeding between two switchgrass August harvest subplots. The meter stick indicates how the two drill rows have expanded into the switchgrass to form a 1-m-wide big bluestem strip

lower leaf area index (LAI) than Cave-in-Rock [20], which may indicate that Trailblazer has a more open canopy that is more prone to encroachment than Cave-in-Rock.

Big bluestem density was greatest in plots receiving no N fertilizer and least in plots receiving 120 kg N ha^{-1} averaged across cultivars and harvest dates. Conducting paired comparisons of the three N rates indicates that big bluestem density was greater in 0 N than 60 and 120 kg N ha^{-1} rates and 60 N was greater than 120 kg N ha^{-1} rate. On average, big bluestem density was more than 17 times greater in 0 N plots than in plots receiving 120 kg N ha^{-1}. In both cultivars and harvest dates, big bluestem density declined as N rate increased and mirrored the findings of Tilman and Wedin [21] that big bluestem is a better N scavenger in low N environments. Switchgrass apparently requires a higher N environment to prevent big bluestem encroachment into established switchgrass stands and suggests that big bluestem can better exploit low N environments than switchgrass. The strong rhizomes and ability to thrive in low N environments helps explain why big bluestem dominates many tallgrass prairie environments [21].

The harvest date main effect was significant ($P<0.01$) for big bluestem encroachment and big bluestem density was greatest in plots harvested in August. Repeated annual harvests in August resulted in switchgrass stands with more than two times greater big bluestem density than areas repeatedly harvested after frost. This result supports the management recommendations to harvest switchgrass for biomass energy once each year after frost to maintain quality switchgrass stands for 5 to 10 years [2, 6].

The interaction of switchgrass cultivar and harvest date was significant ($P<0.01$; Table 2) with cultivars responding differently to harvest date for big bluestem encroachment. Cave-in-Rock harvested in August had four times greater big bluestem density than Cave-in-Rock harvested after frost, whereas Trailblazer had no differences across harvest dates (Table 2). However, Trailblazer harvested in August had two times greater big bluestem density than Cave-in-Rock harvested in August and Trailblazer harvested after frost had seven times greater big bluestem density than Cave-in-Rock harvested after frost (Table 2). As discussed previously, these differences likely are due to differences in canopy architecture between Trailblazer (thinner canopy) and Cave-in-Rock (thicker canopy).

The interaction of switchgrass cultivar and N fertilizer rate was significant ($P<0.01$; Table 3) for big bluestem encroachment. Cave-in-Rock fertilized with 0 N had similar big bluestem density to Trailblazer fertilized with 0 and 60 kg N and Cave-in-Rock fertilized with 60 kg N had similar big bluestem density to Trailblazer fertilized with 120 kg N (Table 3). The greatest difference was in Cave-in-Rock fertilized with 120 kg N, which had virtually no big bluestem present. The previously discussed cultivar differences appear to be exacerbated under changing N rates. Additionally, as indicated previously in the fertilizer discussion, switchgrass appears to require a higher N environment to prevent big bluestem encroachment into established switchgrass stands, but the response is not consistent across switchgrass cultivars.

The interaction of harvest date and N fertilizer rate was significant ($P<0.01$; Table 4) for big bluestem encroachment. Big bluestem density was greatest in plots receiving 0 N regardless of harvest date. Regardless of N rate, harvesting after frost generally resulted in a numerically lower big bluestem density. Big bluestem density was nearly identical for plots harvested in August or after frost and fertilized with 60 kg N. However, harvesting in August and applying 120 kg N had six times greater big bluestem density than harvesting after frost and applying 120 kg N (Table 4). These harvest date and fertilizer interactions are visually evident in Figs. 2 and 3. In Fig. 2, Trailblazer switchgrass receiving 120 kg N ha^{-1} and harvesting at anthesis each year has extensive encroaching big bluestem from the seeded drill rows and invading big bluestem in the middle of the split-plot, as well as

Table 2 Big bluestem encroachment into Cave-in-Rock and Trailblazer switchgrass harvested once per year in August or after frost following 10 years of management for bioenergy near Ithaca, NE

Cultivar	Harvest date	Big bluestem density (no. of plants m^{-2})
Cave-in-Rock	August	0.25±0.06 a*
	After frost	0.06±0.02 b
Trailblazer	August	0.50±0.10 c
	After frost	0.48±0.10 c

Least square means±standard error are averaged across fertilizer treatments and field replicates. Sampling area was a 1-m×30-m transect in each treatment

*Values followed by different letters indicate significant differences at the Bonferroni adjusted P of ≤0.05

Table 3 Big bluestem encroachment into Cave-in-Rock and Trailblazer switchgrass fertilized with 0, 60, or 120 kg N ha^{-1} following 10 years of management for bioenergy near Ithaca, NE

Cultivar	N fertilizer rate (kg N ha^{-1})	Big bluestem density (no. of plants m^{-2})
Cave-in-Rock	0	0.85±0.16 a*
	60	0.21±0.05 b
	120	0.01±0.006 c
Trailblazer	0	0.89±0.17 a
	60	0.68±0.13 a
	120	0.19±0.05 b

Least square means±standard error are averaged across harvest dates and field replicates. Sampling area was a 1-m×30-m transect in each treatment

*Values followed by different letters indicate significant differences at the Bonferroni adjusted P of ≤0.05

Table 4 Big bluestem encroachment into switchgrass fertilized with 0, 60, or 120 kg N ha^{-1} and harvested once per year in August or after frost following 10 years of management for bioenergy near Ithaca, NE

Harvest date	N fertilizer rate (kg N ha^{-1})	Big bluestem density (no. of plants m^{-2})
August	0	0.97±0.18 a*
	60	0.39±0.08 b
	120	0.12±0.04 c
After frost	0	0.78±0.15 a
	60	0.38±0.08 b
	120	0.02±0.008 d

Least square means±standard error are averaged across cultivars and field replicates. Sampling area was a 1-m×30-m transect in each treatment

*Values followed by different letters indicate significant differences at the Bonferroni adjusted *P* of ≤0.05

suppressed switchgrass growth. In contrast, in Fig. 3, Cave-in-Rock switchgrass receiving 120 kg N ha^{-1} and harvesting after frost each year lacks visual evidence of big bluestem and has robust switchgrass growth. These data and visual evidence, in addition to the earlier discussions on cultivars, N fertilizer rates, and harvest dates indicate that switchgrass cultivars and management practices affect switchgrass stand invasion by other species and suggest that broad conclusions should not be based on single cultivars.

Smooth Bromegrass and Intermediate Wheatgrass

Plots harvested in August had greater smooth bromegrass density than plots harvested after killing frost ($P<0.01$). Smooth bromegrass density averaged 0.40 mature plants m^{-2} in August-harvested plots and only 0.03 mature plants m^{-2} in plots harvested after a killing frost. Smooth bromegrass occurred in 17 of the 36 transects. Smooth bromegrass, a strongly rhizomatous C_3 perennial grass, is a common invader of C_4 grass dominated tallgrass prairie [22]. It likely has a greater density on August-harvested switchgrass sites in response to the relatively open canopy in late summer and early autumn, slow switchgrass regrowth following summer harvest, and the potentially reduced vigor of switchgrass plants harvested in August compared with those harvested after dormancy. Although smooth bromegrass invasion reduces switchgrass yield, smooth bromegrass can be removed from switchgrass by applying glyphosate [*N*--(phosphonomethyl)glycine] in autumn following warm-season grass senescence and harvest, or suppressed with prescribed burning in the spring if adequate residue remains for burning [22]. After these data were collected in late autumn 2009, the Trailblazer plots were sprayed with glyphosate and cropped in glyphosate-tolerant soybeans for two growing seasons to convert these plots to “Liberty” a higher yielding bioenergy-specific switchgrass strain.

Intermediate wheatgrass, a weakly rhizomatous C_3 perennial grass, has a similar growth form to switchgrass and was an infrequent invader of switchgrass. Although it was present at the site, it occurred only in 4 of the 36 transects, all in Trailblazer, but there was no difference between cultivars for smooth bromegrass and intermediate wheatgrass encroachment. This limited occurrence of intermediate wheatgrass indicates it likely has a similar competitive ability to switchgrass. Monocultures of intermediate wheatgrass in Oklahoma were invaded by surrounding C_4 grasses after only three production years [23], supporting that it is less competitive than many of the native C_4 grasses, especially where precipitation is adequate.

Fig. 2 Trailblazer switchgrass following 10 years of management for biomass energy that included the application of 120 kg N ha^{-1} and harvesting in early August each year. Notice the encroaching big bluestem flowering stalks in the seeded rows to the right and left, the invading big bluestem in the middle of the split-plot, and the suppressed growth of switchgrass. Photo was taken 13 August 2009 prior to harvest in August

Fig. 3 Cave-in-Rock switchgrass following 10 years of management for biomass energy that included the application of 120 kg N ha^{-1} and harvesting after frost each year. Notice the lack of big bluestem flowering stalks and the robust switchgrass growth. Photo was taken 13 August 2009 prior to harvest after frost

Conclusions

This study provided a unique opportunity to evaluate the competitive ability and persistence of switchgrass after 10 years of production under different bioenergy management scenarios. Although many ecologists have expressed concern about switchgrass invading nontarget sites, this study demonstrates the inverse; switchgrass is invaded by other grass species. These data demonstrate that the competitive ability of switchgrass can be suppressed by poor management, making switchgrass prone to invasion by both C_3 and C_4 grasses. As indicated previously, there was no evidence that switchgrass from this study invaded adjacent field and border areas after 10 years of biomass production. Fertility and harvest management appear to dictate which grass species or grass functional groups will invade switchgrass. Applying no N fertilizer resulted in the increase of other warm-season grasses (especially big bluestem), the increase of cool-season grasses, and the decline of switchgrass stands. These results support the current management recommendations for switchgrass in the region and reiterate the importance of management to stand persistence. Applying at least 60 kg N ha^{-1} was adequate N to meet switchgrass growth demands, limited stand invasion by other grasses, and maintained vigorous switchgrass stands. Harvesting switchgrass in August for 10 years with no N fertilizer input caused switchgrass stands to decline and resulted in a nearly complete stand replacement with cool-season grasses, especially smooth bromegrass. Harvesting switchgrass stands after a killing frost resulted in fewer invasions by other regionally aggressive grasses. However, variable responses across cultivars indicate the need for additional research on bioenergy specific cultivars such as Liberty.

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