Switchgrass, Big Bluestem, and Indiangrass Monocultures and Their Two- and Three-Way Mixtures for Bioenergy in the Northern Great Plains

C. O. Hong · V. N. Owens · D. K. Lee · A. Boe

Abstract High yielding, native warm-season grasses could be used as renewable bioenergy feedstocks. The objectives of this study were to determine the effect of warm season grass monocultures and mixtures on yield and chemical characteristics of harvested biomass and to evaluate the effect of initial seeding mixture on botanical composition over time. Switchgrass (*Panicum virgatum* L.), indiangrass [*Sorghastrum nutans* (L.) Nash], and big bluestem (*Andropogon gerardii* Vitman) were planted as monocultures and in all possible two- and three-way mixtures at three USA locations (Brookings and Pierre, SD and Morris, MN) during May 2002. Biomass at each location was harvested after a killing frost once annually from 2003 to 2005. Total biomass yield significantly increased with year at all locations. Switchgrass monocultures or mixtures containing switchgrass generally out-yielded big bluestem or indiangrass in monocultures or the binary mixture. Cellulose and hemicellulose concentrations were higher in 2004 and 2005 compared with 2003. Switchgrass or mixtures containing switchgrass tended to have less cellulose than either big bluestem or indiangrass. Results were more variable for total N, lignin, and ash. Switchgrass was the dominant component of all mixtures in which it was present while big bluestem was dominant when mixed with indiangrass.

Indiangrass was maintained only in monocultures and declined over years when grown in mixtures at all locations. Our results indicated if biomass yield in the northern Great Plains is a primary objective, switchgrass should be a component of binary or tertiary mixtures that also contain big bluestem and/or indiangrass.

Keywords Bioenergy · Biomass · Monocultures · Warm-season grasses · Warm-season mixtures

Abbreviations
N   Nitrogen
NDF   Neutral detergent fiber
ADF   Acid detergent fiber
ADL   Acid detergent lignin
TN   Total nitrogen

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Introduction

Switchgrass, big bluestem, and indiangrass are common warm-season grasses native to the tall grass prairie of North America. High yielding, native warm-season grasses such as these could be used as renewable bioenergy feedstocks. Switchgrass, in particular, has been extensively studied for its value as a forage, conservation, and bioenergy crop [1–6]. Historically, big bluestem and indiangrass have been evaluated primarily for forage, but recently several groups have assessed their potential as bioenergy crops [7–9]. However, big bluestem and indiangrass have not been adequately tested for biomass in the Northern Great Plains. Native grasses such as these offer a number of distinct benefits including (1) increased nitrogen (N) and water use efficiency compared to cool-season perennial grasses [10]; (2) improved soil conservation and quality [3, 11]; (3) reduced greenhouse gas emissions [12]; (4) carbon sequestration [2, 11, 13, 14]; and (5) the ability to perform on

poorer land such as that enrolled in the Conservation Reserve Program [15].

Recent experiments showed that species-rich grasslands have greater productivity [16, 17] and reduced year-to-year variability of aboveground biomass [18]. However, some scientists have suggested that the productivity and stability of ecosystems do not depend on the number of species [19, 20]. Tilman et al. [21] reported that high-diversity grasslands grown for bioenergy were 238 % higher yielding than monocultures after a decade. In further evaluations of this data, DeHaan et al. [22] concluded that breeding programs focused on grass/legume bicultures may provide greatest early benefits in low-input systems since biomass production of legume/C$_4$ grass bicultures was similar to diverse polycultures (16 species). In contrast, Schmer et al. [23] found that switchgrass managed for high yield produced 93 % more net energy yield than seeded, low input, high diversity prairie mixtures. In previous work in South Dakota, USA, Mulkey et al. [24] found that mixtures of switchgrass and big bluestem grown in marginal soil were well suited for sustainable biomass energy production. Furthermore, N requirements of these mixtures were relatively low (<50 kg ha^{-1}), thus reducing production input costs.

Based on previous work, we hypothesized that (1) the relative yield of monocultures would be greater than simple two- and three-way mixtures of three native grasses; (2) the chemical characteristics of selected monocultures and mixtures would be similar; and (3) the botanical composition of mixtures in different environments would shift over time, particularly in mixtures containing indiangrass. The objectives of this study were to determine the effect of entry (monocultures or simple mixtures) on yield and chemical characteristics of harvested biomass and to evaluate the effect of initial seeding mixture on botanical composition over time.

Materials and Methods

Site Description

This research was conducted at three locations from 2002 to 2005. The first location was near Brookings, SD, USA (44°19′11″ N; 96°45′45″ W) on a Vienna silt loam (fine-loamy, mixed, Udic Haploborolls) with 2-6 % slope; the second location was

approximately 30 km east of Pierre, SD, USA (44°17′7″ N; 100°0′31″ W) on a Sully silt loam (coarse-silty, mixed, mesic Typic Haplustoll) with 0–2 % slope; and the third location was near Morris, MN, USA (45°35′35″ N; 95°53′7″ W) on a Sioux gravelly sandy loam (sandy skeletal, mixed, Udorthentic Haploboroll) with 0–2 % slope. Henceforth, these locations will be referred to as Brookings, Pierre, and Morris. Soil samples were collected before planting to determine selected chemical and physical properties in the top 30 cm for each location (Table 1).

Experimental Design and Field Management

'Sunburst' switchgrass, 'Bison' big bluestem, and 'Tomahawk' indiangrass were planted as monocultures and in all two- and three-way mixtures on 15 May 2002, 16 May 2002, and 21 May 2002, at Brookings, Pierre, and Morris, respectively. Seeding rate for monoculture stands was 6.7, 7.9, and 7.9 kg PLS ha^{-1} for switchgrass, big bluestem, and indiangrass, respectively. Seeding rate of each species in the two- and three-way mixtures was 50 and 33 % of the monoculture seeding rate, respectively. Plots were planted with a Truax$^{(T)}$ no-till drill (Truax Co. Inc., New Hope, MN) with 20-cm row spacing. The experimental design consisted of a randomized complete block with three replications. Individual plot size was 5.2 m wide and 9.1 m long. Warm-season grasses were harvested around a killing frost once each year in 2003, 2004, and 2005. Harvest dates were 21, 14, and 20 October in 2003, 2004, and 2005, respectively at Brookings; 8, 21, and 18 October in 2003, 2004, and 2005, respectively at Pierre; and 15, 21, and 26 October in 2003, 2004, and 2005, respectively at Morris. Fertilizer was not applied at any location during the study.

Determination of Yield and Botanical Composition

Yield was determined by harvesting a 1.1-m wide by 5.1-m long swath through the center of each plot with a sickle bar mower at a height of about 12 cm. Two 0.19-m^2 subsamples were hand-clipped from each plot before harvest for further analyses. Subsamples were individually separated into switchgrass, big bluestem, indiangrass, and grassy and broadleaf weeds for botanical composition. Separated samples were weighed, dried at 60 °C for 48 h in a forced-air oven, and reweighed to determine yield and botanical composition on a

Table 1 Selected chemical and physical properties in the top 30 cm at Brookings, SD, Pierre, SD, and Morris, MN at initiation of research in 2002

Site	pH	BD gcm^{-3}	SOC gkg^{-1}	Total N	NO$_3$–N mgkg^{-1}	Clay gkg^{-1}	Silt	Sand
Brookings	7.7	1.3	21.4	1.62	8.33	281	436	283
Pierre	7.0	1.1	32.3	3.08	20.32	182	691	127
Morris	7.6	1.3	36.9	2.99	16.16	299	300	401

BD soil bulk density, *SOC* soil organic carbon

Table 2 Mean monthly and annual precipitation (millimeters) for each harvest year at Brookings, SD, Pierre, SD, and Morris, MN

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
Brookings													
2003	5.8	5.8	2.5	49.5	69.6	83.8	70.1	56.1	53.1	27.4	8.1	7.4	439.4
2004	8.9	9.4	29.2	41.1	157.7	68.1	111.0	23.1	157.7	14.5	11.7	2.3	634.7
2005	9.4	16.8	13.7	47.0	96.3	152.1	88.1	89.4	194.3	66.8	30.7	36.6	841.2
30-Year average	8.6	10.2	32.8	51.6	74.9	107.4	79.0	74.7	63.0	45.2	25.4	6.6	579.4
Pierre													
2003	9.9	3.6	13.2	85.9	48.5	108.5	30.0	8.9	27.7	16.5	2.8	0.0	355.3
2004	2.0	15.5	68.6	2.5	72.6	56.1	61.5	63.5	144.5	48.5	15.2	0.8	551.4
2005	1.3	4.3	12.4	79.5	93.2	96.0	6.9	18.5	27.9	11.7	7.9	7.4	367.0
30-Year average	10.9	12.2	28.7	52.8	72.9	89.4	66.5	42.9	39.6	31.0	13.2	14.0	474.2
Morris													
2003	8.9	6.6	11.2	50.5	87.9	183.9	125.5	17.8	73.9	24.4	14.5	11.4	616.5
2004	14.7	18.5	38.6	27.7	132.3	106.4	88.6	53.1	151.9	57.4	13.2	5.8	708.4
2005	42.2	17.8	7.4	71.4	55.4	173.0	76.5	91.9	97.3	66.8	67.6	32.3	799.3
30-Year average	17.8	17.0	29.7	58.2	74.9	100.1	93.7	77.0	56.9	44.5	25.1	16.5	611.4

dry matter basis. All herbage was recombined before grinding in preparation for chemical characterization. Herbage samples were ground in a Wiley mill (Thomas-Wiley Mill Co., Philadelphia, PA) to pass a 1-mm screen and reground to uniformity in a Udy-cyclone impact mill (Udy Co., Ft. Collins, CO) with a 1-mm screen.

Chemical Analysis

Biomass chemical composition analysis was determined by the method described by Mulkey et al. [15]. Concentrations of neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), and total nitrogen (TN) were predicted for all samples using near infrared reflectance spectroscopy (NIRS Model 5000; Foss NIRSystems, Silver Springs, MD)

based on a calibration data set of 174 samples representing all harvest years [25]. A set of 30 samples was used for cross-validation. Calibration and validation statistics were generated using WinISI (Version 1.5) system software (Infrasoft International LLC., State College, PA). For calibration and validation samples, NDF and ADF were determined sequentially using an Ankom200 Fiber Analyzer (ANKOM Technology Corp., Fairport, NY), ADL was determined with a Daisy II Incubator (ANKOM Technology Corp., Fairport, NY), and TN was quantified using a Vario Max CNS elemental analyzer (Elementar Instrument, Mt. Laurel, NJ). Hemicellulose was then calculated as the difference between NDF and ADF and cellulose as the difference between ADF and ADL. Ash concentrations were determined using the methods described by Undersander et al. [26].

Table 3 Analysis of variance and probability values for yield and chemical composition of big bluestem (BB), indiangrass (IND), and switchgrass (SWG) grown in monocultures and two- and three-way mixtures at Brookings, SD, Pierre, SD, and Morris, MN over 3 years

Source of variation	df	Yield	TN	Cellulose	Hemicellulose	Lignin	Ash
Brookings							
Block	2	NS	NS	NS	NS	NS	NS
Year	2	<0.001	<0.001	<0.001	NS	NS	0.037
Species	6	<0.001	NS	<0.001	<0.001	NS	<0.001
Species × year	12	NS	NS	NS	NS	NS	0.008
Pierre							
Block	2	0.002	NS	NS	NS	NS	NS
Year	2	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Species	6	<0.001	NS	<0.001	NS	NS	NS
Species × year	12	NS	0.034	NS	NS	NS	NS
Morris							
Block	2	<0.001	NS	NS	<0.001	0.004	0.007
Year	2	<0.001	NS	<0.001	<0.001	<0.001	<0.001
Species	6	NS	NS	<0.001	<0.001	0.002	NS
Species × year	12	NS	0.021	NS	0.010	NS	NS

TN total nitrogen, *NS* not significant at 0.05 level of probability

Statistical Analysis

Yield, chemical composition, and botanical composition data were analyzed by analysis of variance using PROC MIXED in SAS [27]. Species composition data were arcsine transformed before analysis to ensure a normal distribution [28]. A least significance difference was used to separate mean effects when the appropriate F test was significant ($p=0.05$). Harvest year, entry, and location were considered to be fixed effects, while replication was treated as random. Due to numerous location×year and location×entry interactions, each location was analyzed separately. The data were subjected to correlation analysis to determine the relationship between precipitation and yield of big bluestem, indiangrass, and switchgrass grown in monocultures and two- and three-way mixtures across three locations.

Results

Biomass Production

Monthly and total precipitation amounts for each location from 2003 to 2005 are presented in Table 2. Annual precipitation was above the 30-year average at all locations in 2004 and at Brookings and Morris in 2005. With the exception of the Pierre location in 2005, biomass production was highest when total annual precipitation was equal to or greater than the 30-year average.

There was no entry×year interaction for yield at any location, but yield differed by year at all locations (Table 3). Biomass was highest in 2005 at all locations, although yields
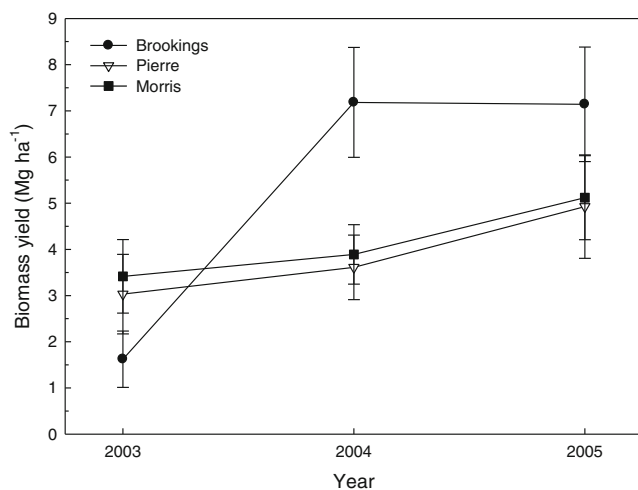
did not differ in 2004 and 2005 at Brookings (Fig. 1). Total production gradually increased with year at Pierre and Morris while average yield increased more than four times at Brookings between 2003 (1.62 Mgha^{-1}) and 2004 (7.18 Mgha^{-1}), and was sustained at 7.14 Mgha^{-1} in 2005.

Entry significantly affected biomass yield at Brookings and Pierre but not at Morris (Table 3). Despite the lack of an entry
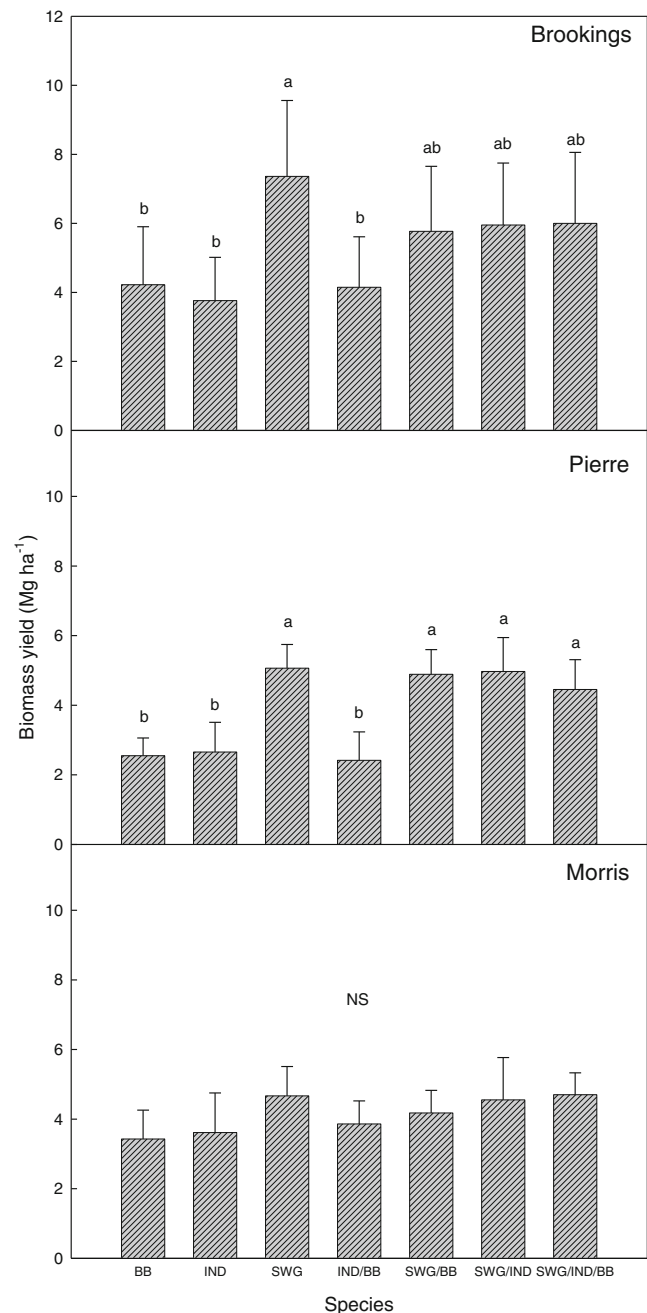

Fig. 1 Total biomass yields of grass monocultures and mixtures in response to harvest years at Brookings, SD, Pierre, SD, and Morris, MN, USA. Values are averaged across monocultures and mixtures and *vertical bars* represent standard errors. Least significant differences at $p>0.05$ level of probability were 1.13, 0.97, and 0.85 Mgha^{-1} for Brookings, Pierre, and Morris, respectively

Fig. 2 Average biomass production of big bluestem (*BB*), indiangrass (*IND*), and switchgrass (*SWG*) grown in monocultures and two- and three-way mixtures at Brookings, SD, Pierre, SD, and Morris, MN, USA. Values are averaged across years and *vertical bars* represent standard errors. *Different letters above bars* denote significant difference at $p>0.05$ level of probability

effect at Morris, the yield pattern was similar at all locations (Fig. 2). No monoculture entry produced more biomass than switchgrass at Brookings and Pierre, and while not significantly different, the same pattern was observed at Morris. Big bluestem and indiangrass yields were similar to each other in monocultures and in their two-way mixture at all locations. Combining switchgrass with big bluestem, indiangrass, or big bluestem + indiangrass resulted in yields that were more similar to switchgrass than either big bluestem or indiangrass monocultures at Pierre. Mixtures containing switchgrass were equal in yield to both switchgrass and to indiangrass or big bluestem monocultures at Brookings and Morris.

Chemical Composition

Total N concentration varied by year at Brookings and Pierre and there was a year×entry interaction at Pierre and Morris (Table 3). Total N ranged from 1.9 to 11.2, 4.0 to 12.4, and 1.8 to 3.1 g kg^{-1} at Brookings, Pierre, and Morris, respectively (data not shown). Year of growth generally had a greater effect on TN than did entry at all locations despite the year × entry interaction at Pierre and Morris.

Cellulose concentration ranged from 294 to 420, 391 to 485, and 387 to 482 g kg^{-1} in 2003, 2004, and 2005, at Brookings, Pierre, and Morris, respectively, during the study (Fig. 3). Year and entry affected cellulose concentration at all locations. There was an effect of entry at Brookings; year at Pierre; and year, entry, and year × entry interaction at Morris for hemicellulose (Table 3). In general, both constituents increased over time (Fig. 3) as the proportion of desirable grass increased. Cellulose concentration was typically lower in switchgrass monocultures and in mixtures containing switchgrass, but the same pattern was not observed for hemicellulose (Fig. 4).

Lignin varied significantly by year at Pierre and Morris and by entry at Morris (Table 3). Lignin concentration was higher in 2004 than either 2003 or 2005 at Pierre and Morris, but remained relatively constant across years at Brookings (Fig. 3).

Ash concentration ranged from 45 to 86 g kg^{-1} among locations, but varied from year to year (Table 3). Ash concentration did not differ in 2003 and 2004 at any location, but it decreased from 2004 to 2005 at Brookings and Pierre and increased at Morris. There was a
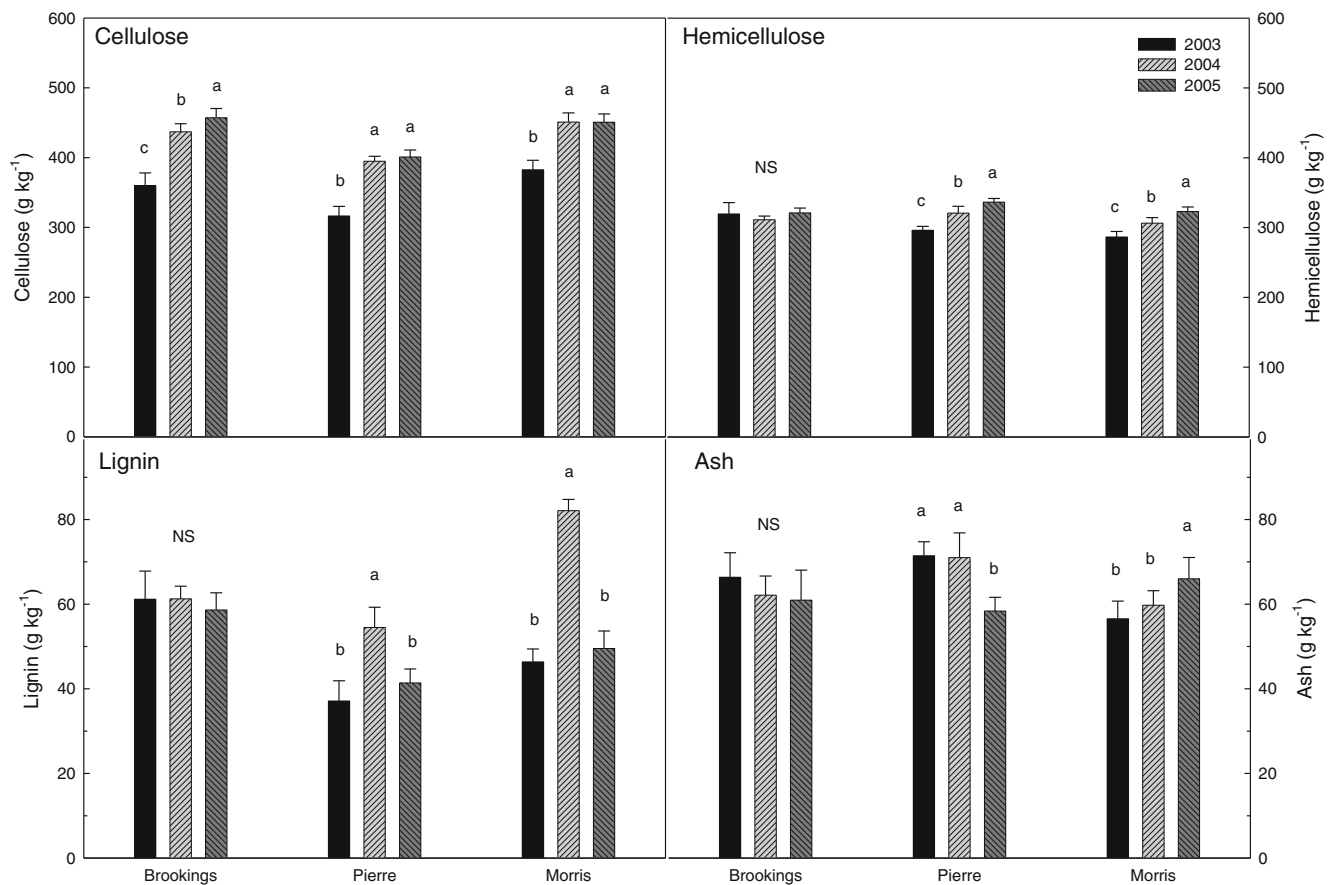

Fig. 3 Average concentration of cellulose, hemicelluloses, lignin, and ash in biomass harvested at Brookings, SD, Pierre, SD, and Morris, MN, USA. Values are averaged across monocultures and mixtures and vertical bars represent standard errors. Different letters on bars denote significant difference at $p>0.05$ level of probability
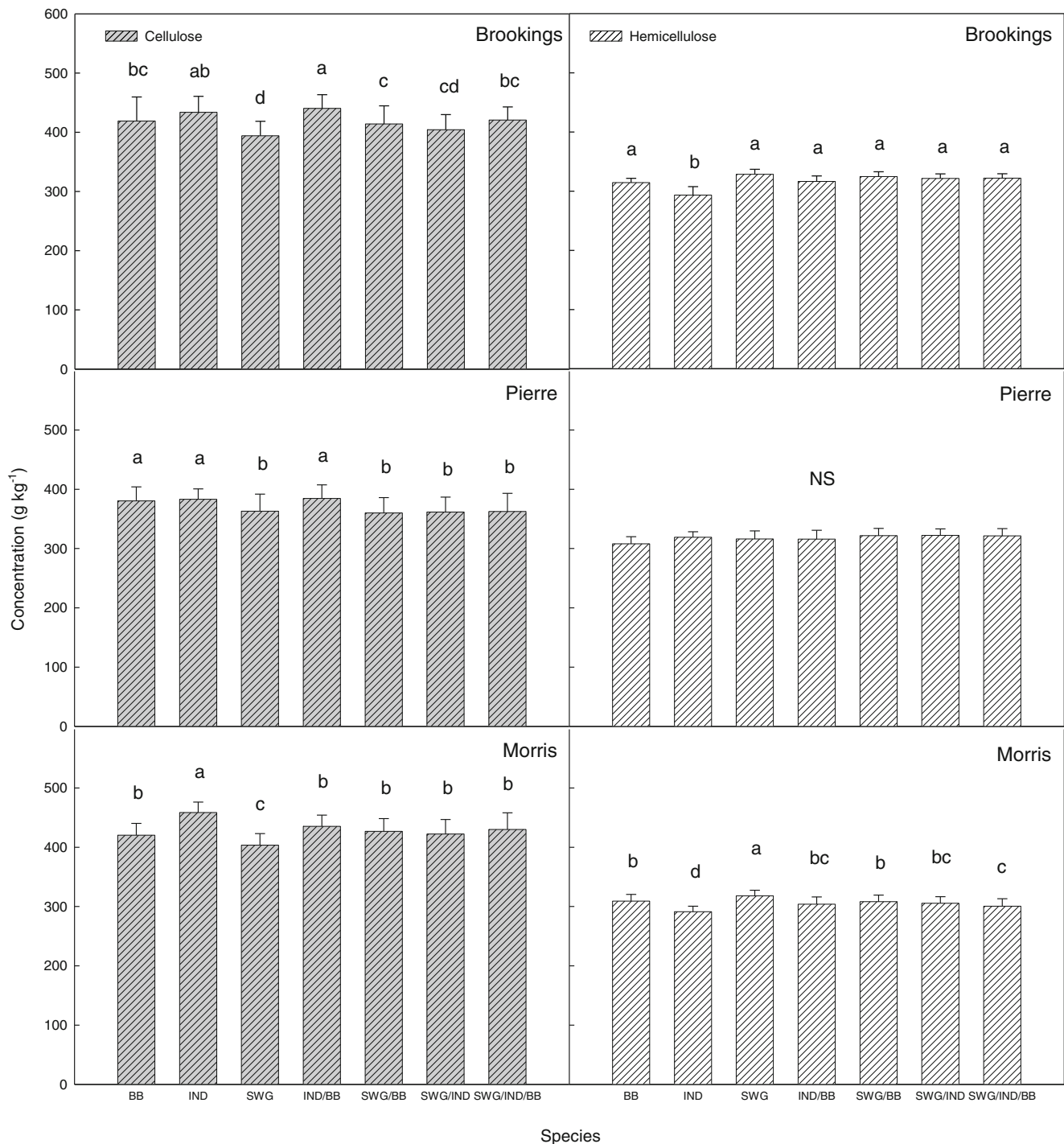
Fig. 4 Average concentration of cellulose and hemicellulose of big bluestem (*BB*), indiangrass (*IND*), and switchgrass (*SWG*) grown in monocultures and two- and three-way mixtures at Brookings, SD, Pierre, SD, and Morris, MN, USA. Values area averaged across years and *vertical bars* represent standard errors. *Different letters above bars* denote significant difference at *p*>0.05 level of probability

significant entry × year interaction for ash at Brookings (Table 3), due to the fact that ash concentration of switchgrass, indiangrass, and switchgrass + indiangrass gradually increased with year while that of monoculture big bluestem and big bluestem mixtures decreased (data not shown).

Botanical Composition

Composition of harvested biomass changed between 2003 and 2005 (Figs. 5, 6, and 7). Native grass production was negatively affected by weed encroachment in 2002 (the establishment year when no biomass was harvested) and in
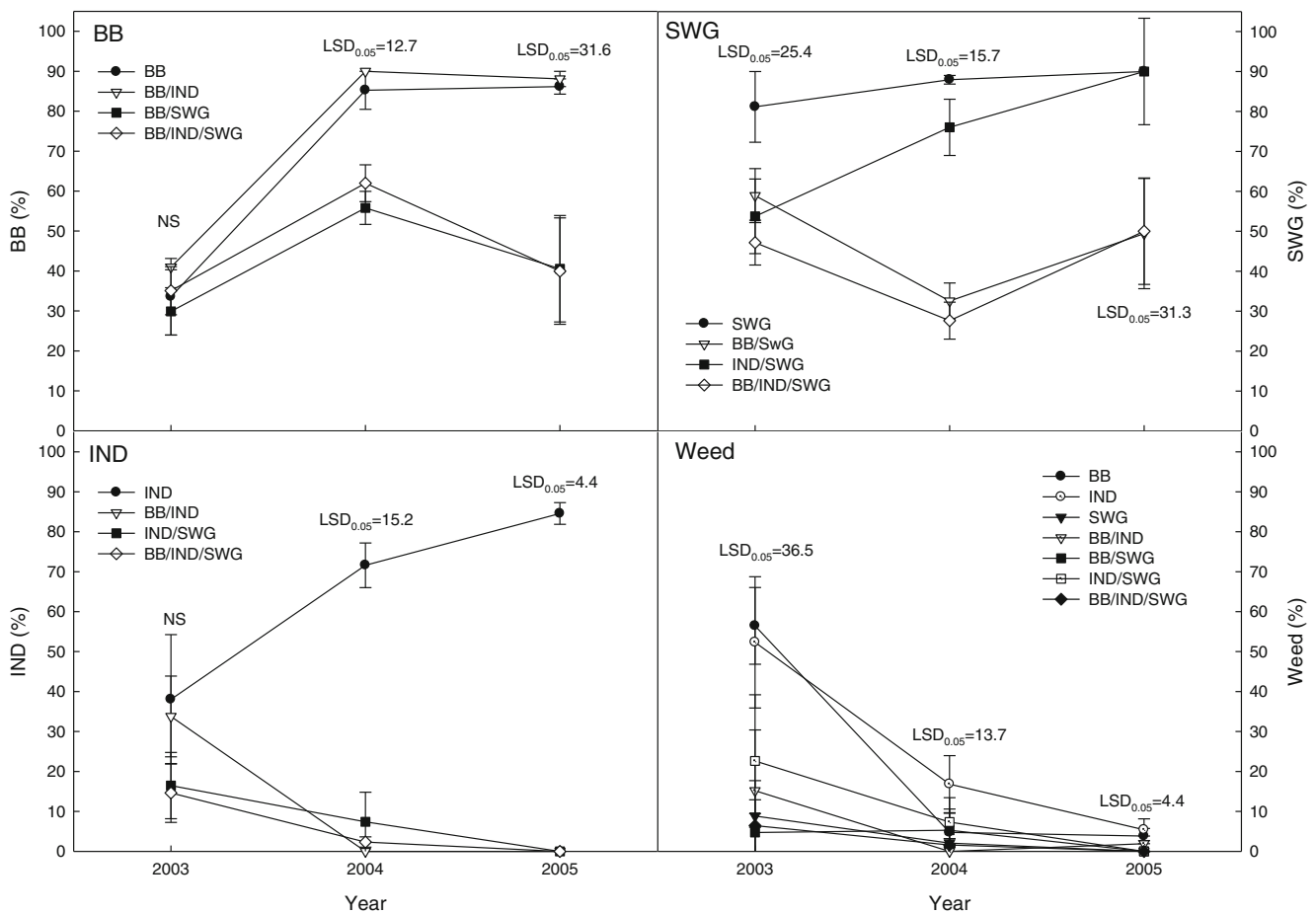
Fig. 5 Percent big bluestem (*BB—upper left panel*), indiangrass (*IND —lower left panel*), switchgrass (*SWG—upper right panel*), and weedy species (*WEEDS—lower right panel*) grown in monocultures and two-

and three-way mixtures in harvested biomass at Brookings, SD, USA. *Vertical bars* represent standard errors

2003. By 2004, weed percentage had decreased greatly in most plots and was less than 10 % of total biomass by 2005, particularly in plots containing switchgrass or big bluestem. There was a year × entry interaction for big bluestem, indiangrass, switchgrass, and weeds at Brookings and for big bluestem and indiangrass at Morris (Table 4). Big bluestem percentage increased over time when grown in monoculture or with indiangrass at all three locations (Figs. 5, 6, and 7). The proportion of big bluestem also increased at Brookings and Morris when grown with switchgrass or in the three-way mixtures between 2003 and 2004 but remained constant or decreased slightly from 2004 to 2005. In two-way mixtures of switchgrass and big bluestem and in three-way mixtures of switchgrass, big bluestem, and indiangrass, switchgrass percentage was inversely related to big bluestem composition at all locations (Figs. 5, 6, and 7). The proportion of indiangrass increased at Brookings and Morris but decreased at Pierre when grown alone, and decreased at all locations when grown in any two- or three-way mixtures (Figs. 5, 6, and 7).

There was an entry effect for big bluestem, indiangrass, and switchgrass and year effect for switchgrass and weeds at Pierre (Table 4). Big bluestem percentage was higher in monoculture or with indiangrass than when mixed with switchgrass or switchgrass and indiangrass (Fig. 6). Indiangrass was highest only when grown alone, and represented <10 % of the overall mixture in other mixtures at this location. Switchgrass percentage steadily increased at Pierre whether as a monoculture or in mixtures, always representing >60 % of the total plot weight (Fig. 6).

Discussion

Data from three locations in the northern Great Plains demonstrated that total biomass of native grass monocultures and mixtures generally increased the first 3 years after establishment (Fig. 1). In the Southern Plains, Fuentes and Taliaferro [29] suggested that switchgrass and other perennial grasses would achieve full yield potential the year after establishment if not harvested in the seeding year. While this occurred at
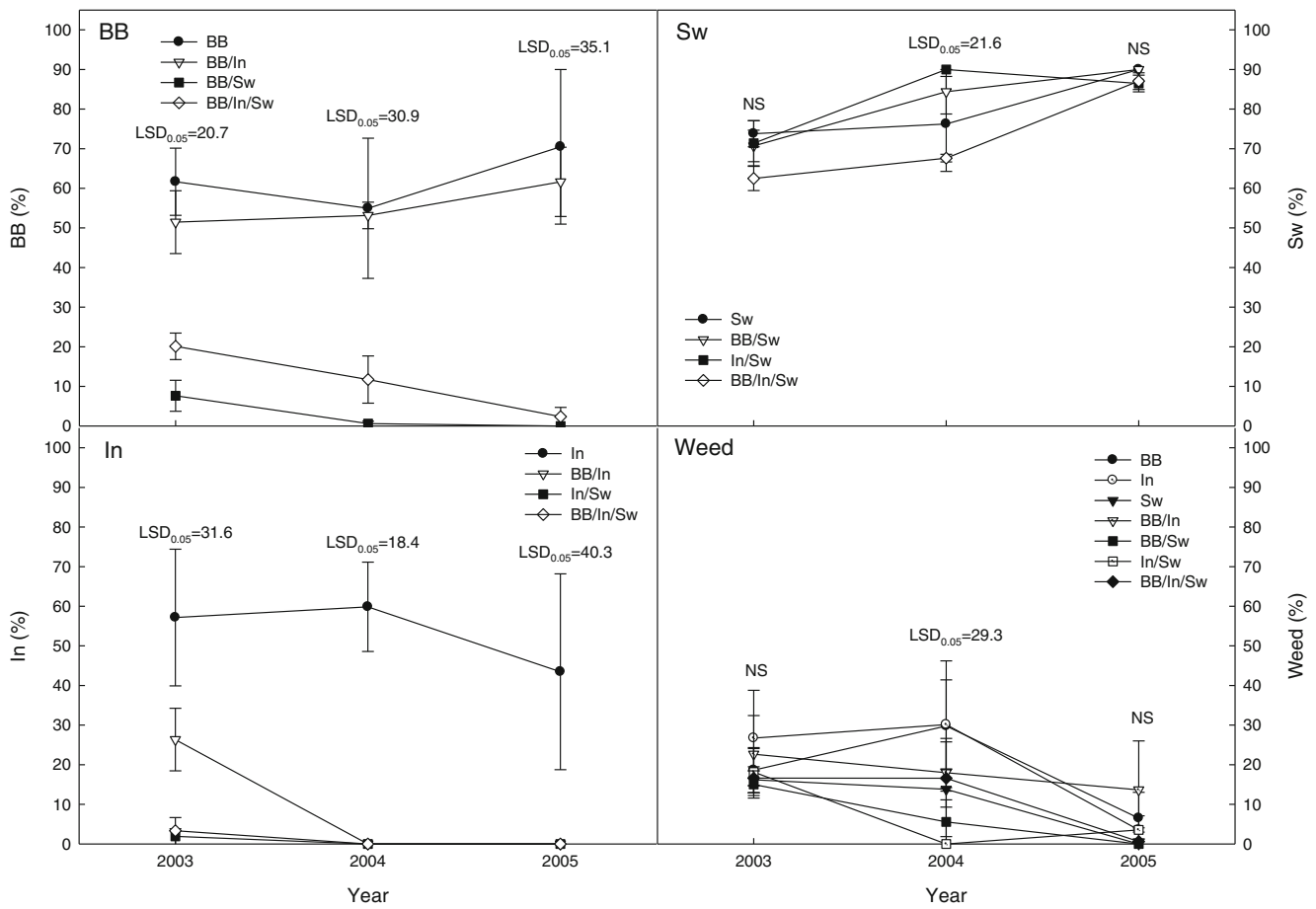
Fig. 6 Percent big bluestem (*BB—upper left panel*), indiangrass (*IND—lower left panel*), switchgrass (*SWG—upper right panel*), and weedy species (*WEEDS—lower right panel*) grown in monocultures and two- and three-way mixtures in harvested biomass at Pierre, SD, USA. *Vertical bars* represent standard errors

Brookings, there was a linear increase in yield during the first 3 years after establishment at Pierre and Morris (Fig. 1).

Soils at Morris were much coarser (gravelly silt loam; Table 1) than at either Brookings or Pierre (silt loam). Therefore, despite having higher precipitation at Morris (Table 2), biomass production may have been limited by the ability of the soil to retain moisture. Pierre received 22 to 54 % less annual precipitation than Morris, yet yield at these two locations was similar across years. On the other hand, Brookings and Morris received similar rainfall amounts in 2004 and 2005 (Table 2), but yield was substantially higher in Brookings compared to Morris (Fig. 1).

Precipitation amount and timing has been shown to affect native grass yield in various regions of the USA [30–32], although other factors such as light and fertility interact with moisture to affect overall yield [30]. Lee and Boe [33] reported a strong linear relationship between April through May precipitation and switchgrass production during 4 years in central South Dakota. In this study, however, there was no significant relationship between April through May precipitation and production of native grass monocultures and mixtures ($r=0.354$ to

0.657) despite the variability in precipitation patterns across the three locations (Table 2). Season long (April–September) precipitation was more closely related to production than other precipitation time periods, but this relationship was significant for big bluestem ($r=0.802**$) and big bluestem + indiangrass ($r=0.749*$) only. Similarly, of four native grasses (big bluestem, indiangrass, switchgrass, and little bluestem [*Schizachyrium scoparium*]) evaluated by Shiflet and Dietz [31] in southeastern Kansas, only big bluestem production was significantly correlated with season long (April–September) precipitation.

Based on previous work, we expect switchgrass and big bluestem yields to be maintained for numerous years if harvested after senescence [15, 24]. Tilman et al. [21] reported that low input high-diversity grasslands had higher biomass production than monocultures. Similarly, Picasso et al. [34] concluded that diversity should be used in designing productive bioenergy systems based on complementary of relatively simple two- to six-species mixtures they evaluated in Iowa. In Oklahoma, Griffith et al. [7] reported monoculture yields (particularly switchgrass) or a binary mixture of old world
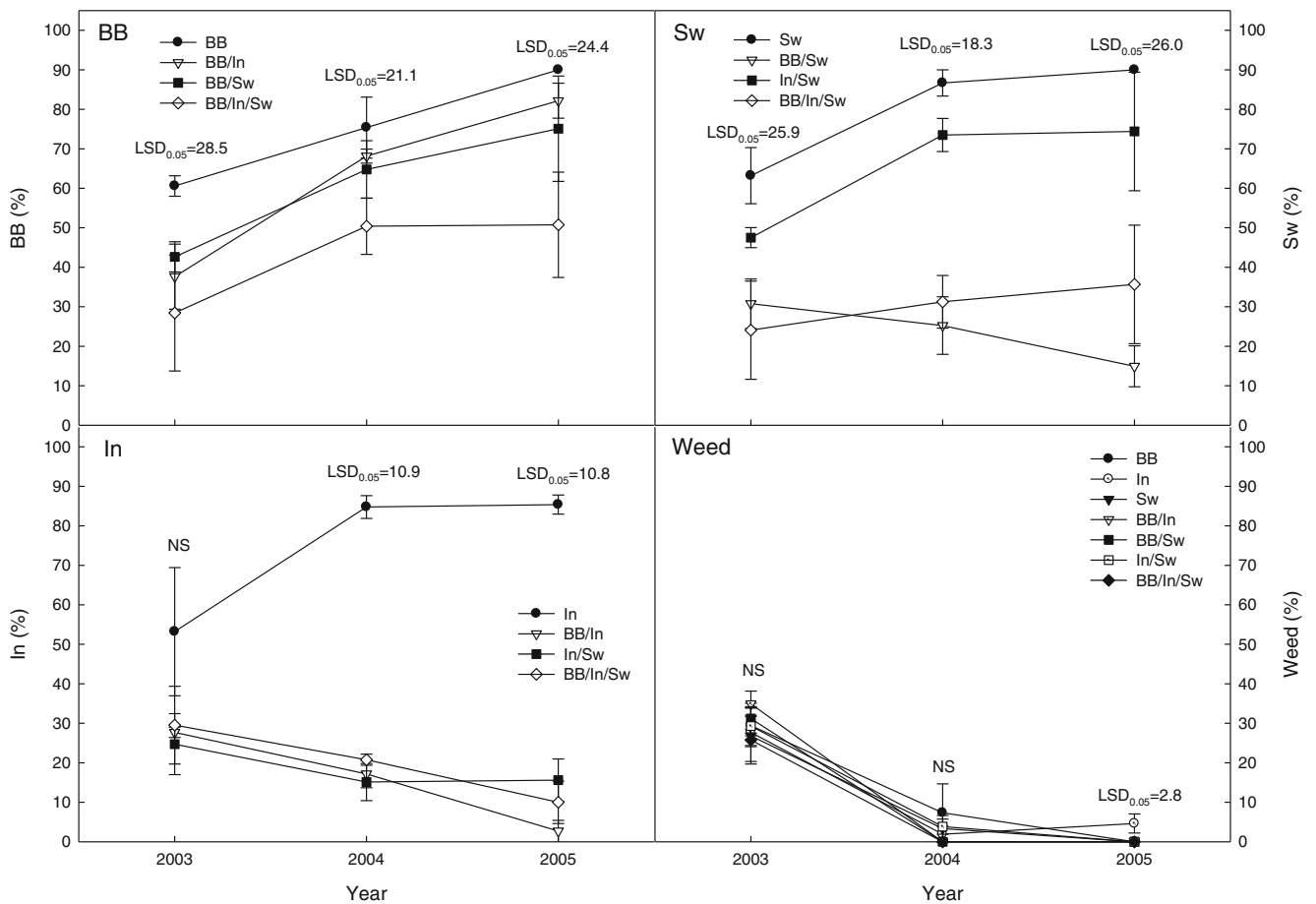
Fig. 7 Percent big bluestem (*BB—upper left panel*), indiangrass (*IND—lower left panel*), switchgrass (*SWG—upper right panel*), and weedy species (*WEEDS—lower right panel*) grown in monocultures and two- and three-way mixtures in harvested biomass at Morris, SD, USA. *Vertical bars* represent standard errors

Table 4 Analysis of variance and probability values for percent big bluestem (BB), indiangrass (IND), and switchgrass (SWG) grown in monocultures and two- and three-way mixtures in harvested biomass at Brookings, SD, Pierre, SD, and Morris, MN

Source of variation	df	BB	IND	SWG	Weed
Brookings					
Block	2	NS	NS	NS	NS
Year	2	<0.001	NS	NS	<0.001
Species	6	<0.001	<0.001	<0.001	<0.001
Year × species	12	<0.001	<0.001	0.010	0.020
Pierre					
Block	2	0.044	NS	NS	0.002
Year	2	NS	NS	0.002	<0.001
Species	6	<0.001	<0.001	<0.001	NS
Year × species	12	NS	NS	NS	NS
Morris					
Block	2	NS	NS	NS	NS
Year	2	<0.001	NS	0.028	<0.001
Species	6	<0.001	<0.001	<0.001	NS
Year × species	12	0.003	<0.001	NS	NS

NS not significant at 0.05 level of probability

bluestem (*Bothriochloa ischaemum* L. King) and alfalfa (*Medicago sativa* L.) to be higher than more complex mixtures. Picasso et al. [35] noted the importance of a "driver" species in several Iowa environments. They defined a driver species as one from which the majority of biomass is obtained whether in monoculture or in polycultures. While high diversity treatments were not included in the current work, from a yield perspective switchgrass seemed to be the most important grass component (e.g., driver species) in the single functional group (i.e., perennial warm-season grasses) mixtures evaluated. At all locations, yield was highest in treatments in which switchgrass was grown alone or as part of the mix. This was true for switchgrass + big bluestem and switchgrass + big bluestem + indiangrass mixtures, despite the fact that big bluestem percentage increased significantly at Brookings and Morris over time.

Annual changes in chemical composition were likely related to two key factors. First, grass yields were generally higher in 2004 and 2005, and it is likely that a greater proportion of harvested biomass was composed of internodes, where lignocellulose accumulates, rather than leaf blades. Secondly, a greater proportion of broadleaf weeds were present in 2003

which may have led to elevated nitrogen concentrations, particularly at Brookings and Pierre. Monoculture switchgrass or mixtures including switchgrass tended to have lower cellulose concentrations than either big bluestem or indiangrass while other chemical constituents were more variable (Fig. 4). Similarly, Waramit et al. [9] reported lower concentrations of cellulose in switchgrass compared with indiangrass and big bluestem harvested during late autumn in Iowa. Despite the variability in cellulose and hemicelluloses concentrations across years, locations, and entries, total production of these structural carbohydrates was generally higher in mixtures in which switchgrass was included since switchgrass was a key component of total biomass (data not shown) and was higher yielding than either big bluestem or indiangrass (Fig. 2).

Indiangrass did not perform well when mixed with either switchgrass, big bluestem, or both species despite the fact that it is co-dominant with these species in the tall grass prairie [36]. Springer et al. [37] also found that indiangrass decreased over time when harvested for forage in mixtures with switchgrass or big bluestem in Oklahoma. These results are also similar to those of Mulkey et al. [24] who found that indiangrass percentage decreased in established native grass mixtures managed for biomass in South Dakota.

Percentage switchgrass and big bluestem were essentially inversely related at all locations, although they were more complementary to each other at Brookings (Fig. 5) and Morris (Fig. 6) than at the drier Pierre (Fig. 7) location where big bluestem represented less than 5 % of total biomass in switchgrass + big bluestem and switchgrass + big bluestem + indiangrass mixtures. Furthermore, switchgrass became more dominant over time in all mixtures at Pierre, thus maintaining yield levels equal to switchgrass monocultures. In previous work, Mulkey et al. [24] reported that percentage switchgrass and big bluestem were comparable in warm-season grass mixtures in south central South Dakota when harvested late in the season while Springer et al. [37] found that switchgrass was more dominant than big bluestem in a mixture of these species harvested for forage in Oklahoma.

While not a highly diverse mixture, a combination of switchgrass and big bluestem appeared to have potential for biomass in the Northern Great Plains since yields were equal to those of switchgrass monocultures. However, switchgrass monocultures or mixtures containing switchgrass consistently out-yielded big bluestem or indiangrass in monocultures or the binary mixture of these two species. Our results indicated if biomass yield in the Northern Great Plains is a primary objective, switchgrass should be a component of binary or tertiary

perennial grass mixtures that also contain big bluestem and/or indiangrass.

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