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Field-scale soil property changes under switchgrass managed for bioenergy

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Abstract

The capacity of perennial grasses to affect change in soil properties is well documented but information on switchgrass (*Panicum virgatum* L.) managed for bioenergy is limited. An on-farm study (10 fields) in North Dakota, South Dakota, and Nebraska was sampled before switchgrass establishment and after 5 years to determine changes in soil bulk density (SBD), pH, soil phosphorus (P), and equivalent mass soil organic carbon (SOC). Changes in SBD were largely constrained to near-surface depths (0–0.05 m). SBD increased (0–0.05 m) at the Nebraska locations (mean = 0.16 Mg m^{-3}), while most South Dakota and North Dakota locations showed declines in SBD (mean = −0.18 Mg m^{-3}; range = −0.42–0.07 Mg m^{-3}). Soil pH change was significant at five of the 10 locations at near surface depths (0–0.05 m), but absolute changes were modest (range = −0.67–0.44 pH units). Available P declined at all sites where it was measured (North Dakota and South Dakota locations). When summed across the surface 0.3 m depth, annual decreases in available P averaged 1.5 kg P ha^{-1} yr^{-1} (range = 0.5–2.8 kg P ha^{-1} yr^{-1}). Averaged across locations, equivalent mass SOC increased by 0.5 and 2.4 Mg C ha^{-1} yr^{-1} for the 2500 and 10 000 Mg ha^{-1} soil masses, respectively. Results from this study underscore the contribution of switchgrass to affect soil property changes, though considerable variation in soil properties exists within and across locations.

Nomenclature:

SOC = soil organic carbon
SBD = soil bulk density
GHG = greenhouse gas emissions
CRP = Conservation Reserve Program

Keywords: biofuel, soil organic carbon, soil property changes, switchgrass

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Introduction

The capacity of perennial grasses to affect change in soil properties is well documented (Follett *et al*., 2001), but soil changes specific to switchgrass managed for bioenergy production is limited with most soil information relegated to soil organic carbon (SOC) (Frank *et al*., 2004; Liebig *et al*., 2005; Anderson-Teixeira *et al*., 2009). Information on dedicated perennial bioenergy crop effects on soil productivity at the field scale is considered a research need (Blanco-Canqui, 2010). Perennial bioenergy crops like switchgrass are projected to reduce US reliance on fossil fuels, reduce greenhouse gas emissions (GHG), and enhance rural economies (McLaughlin *et al*., 2002). Further, perennial bioenergy crops grown on marginal cropland can decrease water pollution, reduce water and wind erosion, and improve wildlife habitat over annual row crops (Blanco-Canqui, 2010).

Switchgrass is a warm-season perennial grass being developed as a major cellulosic feedstock source for bioenergy production (Vogel & Mitchell, 2008). Favor-

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able feedstock costs (Perrin *et al*., 2008) and net energy benefits when grown on marginal lands in the Great Plains have been reported for switchgrass (Schmer *et al*., 2008). Up to 21 million ha is estimated to be rotated into perennial bioenergy crops within the United States (McLaughlin *et al*., 2002). The majority of land dedicated to perennial energy crop production will be on marginal cropland or existing Conservation Reserve Program (CRP) land (McLaughlin *et al*., 2002; Walsh *et al*., 2003). Switchgrass likely will be in a crop rotation for a minimum of 5 years before another crop rotation occurs. The effects of switchgrass managed as a bioenergy crop on soil properties need to be quantified because of their potential effects on long-term switchgrass production stability and on subsequent annual row crop rotations.

Research conducted on working farms can provide critical information regarding agroecosystem effects on agronomic and environmental performance under conditions not available at research stations (Lockeretz & Anderson, 1993). Documented changes in soil properties in on-farm research, then, are valid, and provide necessary confirmation for similar findings from small-scale research plots. On-farm research on perennial bioenergy cropping systems is limited with the majority of data derived from small plot research (Schmer *et al*., 2010). In 2000, an on-farm switchgrass trial was initiated in the Great Plains based on economic data that estimated significant conversion of cropland to perennial bioenergy crops (Walsh, 1998). Research from the on-farm switchgrass trial has resulted in farm-gate feedstock cost estimates (Perrin *et al*., 2008), determination of volumetric SOC dynamics (Liebig *et al*., 2008), switchgrass life-cycle assessment (Schmer *et al*., 2008), and field-scale simulation yield modeling (Kiniry *et al*., 2008). The objective of this study was to quantify field-scale changes in SBD, pH, available phosphorus (P), and equivalent mass SOC under switchgrass bioenergy management. These soil properties were selected for evaluation due to their direct or indirect contributions to soil structural attributes, such as porosity and aggregation (SBD), soil buffering capacity (soil pH), fertility (available P), and biological soil quality, water-holding capacity, and aggregate stability (SOC).

Materials and methods

Experimental sites

Sites in this study were located in states of Nebraska (four fields), South Dakota (four fields), and North Dakota (two fields) across an area based on Major Land Resource Areas that encompasses approximately 30 Mha (Fig. 1). Climate within the region is generally classified as semi-arid to subhumid continental, with cold and dry winters, warm to hot summers, and erratic precipitation (Bailey, 1995). Mean annual precipitation for the study sites ranged from 430 to 699 mm increasing from west to east, while mean annual temperature ranged from 2.7 °C in the north to 12.8 °C in the south (Table 1).

Sites seeded to switchgrass were fields previously used for annual crop production. Field characteristics were such that they would have qualified for enrollment as CRP (Schmer *et al*., 2006). Field size across sites averaged 6.7 ha (range = 3.0–9.5 ha). Sites at Douglas, Lawrence, and Crofton were seeded to switchgrass in 2000, while all other sites were seeded in 2001. Switchgrass was seeded at a rate of 322 pure live seeds (PLS) m^{-2}. Application of nitrogen (N) varied in amount and type across sites based on biomass yield expectations and soil moisture conditions (Schmer *et al*., 2010). Over the 5-year period of the switchgrass stands, site averages of applied N ranged from 31 to 104 $\mathrm{kg\,N\,ha^{-1}\,yr^{-1}}$ (mean = 74 $\mathrm{kg\,N\,ha^{-1}}$) (Schmer *et al*., 2010). With the exception of the establishment year, aboveground biomass was harvested annually and baled. Additional details on site establishment, management, soil classification, and biomass harvest were previously published (Schmer *et al*., 2006, 2010; Liebig *et al*., 2008).

Sampling protocol

To evaluate change in soil properties under switchgrass over time, soil samples were collected from each site on a 5-year time-step. Sites at Douglas, Lawrence, and Crofton were sampled in 2000 and 2005, while all other sites were sampled in 2001 and 2006 (with the exception of the Atkinson site, which was sampled in 2005). Samples were collected in the spring once soils were no longer frozen and surface conditions were dry enough to permit vehicular traffic. In 2000 and 2001, samples were collected immediately before switchgrass planting.

At each site, soil samples were collected from two 60 m transects with three sampling locations each (located approximately 30 m apart), resulting in a total of six sampling locations per site. The geographical position of each sampling location was recorded with a handheld global positioning system receiver with an accuracy of <3 m (Garmin International Inc., Olathe, KS, USA) and supplemental field notes using notable visual landscape attributes. Six of the locations (Streeter, Bristol, Highmore, Crofton, Douglas, and Lawrence) had variable topography and were sampled by landscape position (i.e., shoulder, backslope, footslope). Sampling locations were treated as pseudoreplicates as reviewed by Gomez (1984). Owing to difficulty during initial sample collection at Atkinson, only two locations per transect were sampled.

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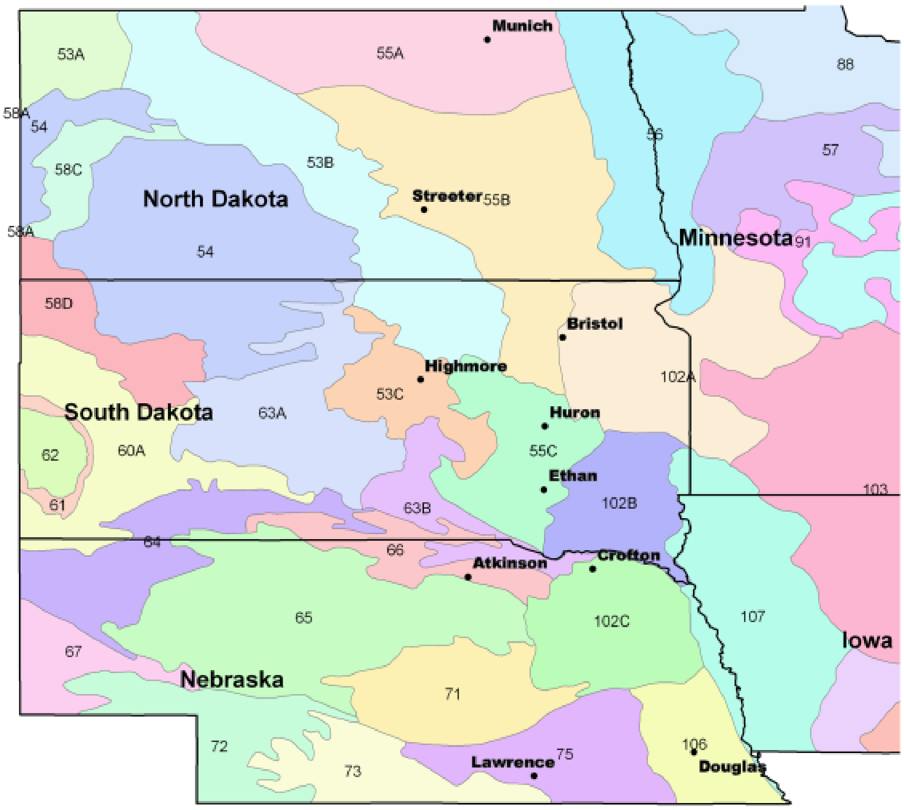

Fig. 1 Location of switchgrass fields managed for bioenergy in the Great Plains region, USA. Corresponding major land resource areas are presented for each location (Munich, 55A-Northern black glaciated plains; Streeter, 55B-Central black glaciated plains; Bristol, 102A-Rolling till prairie; Highmore, 53C-Southern dark brown glaciated plains; Huron, 55C-Southern black glaciated plains; Ethan, 55C-Southern black glaciated plains; Crofton, 102C-Loess plains; Atkinson, 66-Dakota-Nebraska eroded tableland; Douglas, 106-Nebraska and Kansas loess-drift hills; Lawrence, 75-Central loess plains).

Table 1 Mean annual precipitation and temperature by location for switchgrass fields managed for bioenergy production in the Northern Plains

Year	Munich	Streeter	Bristol	Highmore	Huron	Ethan	Crofton	Atkinson	Douglas	Lawrence
Precipitation (mm)										
2000	–	–	–	–	–	–	605	426	658	678
2001	458	396	414	436	680	642	825	716	965	760
2002	516	414	427	293	378	526	553	344	548	612
2003	351	369	518	384	417	479	642	395	579	617
2004	599	562	683	609	755	714	722	564	743	689
2005	577	411	664	473	655	733	–	–	–	–
5-year mean	500	430	541	439	577	619	669	489	699	671
30-year mean	460	434	560	472	531	581	706	627	779	679
Temperature (°C)										
2000	–	–	–	–	–	–	9.2	10.3	11.1	12.8
2001	3.3	5.3	7.2	7.9	7.7	8.2	9.4	10.3	11.2	12.6
2002	2.5	4.7	7.3	8.2	8.3	8.7	9.4	10.3	11.3	12.6
2003	2.6	4.3	6.9	7.9	7.8	8.9	9.1	10.2	10.7	12.1
2004	1.9	4.2	7.0	7.6	8.1	9.2	9.2	10.3	10.7	11.9
2005	3.3	5.3	6.7	8.0	8.7	9.8	–	–	–	–
5-year mean	2.7	4.8	7.0	7.9	7.7	8.2	9.2	10.3	11.1	12.8
30-year mean	3.6	4.3	6.1	6.5	7.4	7.9	8.8	9.1	10.3	11.4

Soil samples were collected using a truck-mounted Giddings hydraulic probe (Giddings Machine Company, Windsor, CO, USA) with an inner tip diameter of 4.2 or 4.4 cm, depending on soil conditions at the time of sampling. Soil depths sampled were 0–0.05, 0.05–0.1, 0.1–0.2, 0.2—0.3, 0.3–0.6, and 0.6–0.9, and 0.9–1.2 m for the Nebraska sites and 0–0.05, 0.05–0.1, 0.1–0.2, and 0.2–0.3 m for the North and South Dakota sites. At each sampling location, seven soil cores were composited at each sampling location for the 0–0.05 and 0.05–0.1 m depths, five soil cores for the 0.1–0.2 and 0.2–0.3 m depths, and two soil cores for the 0.3–0.6, 0.6–0.9, and 0.9–1.2 m depths. Following collection, each sample was saved in a double-lined plastic bag, stored in coolers while in transit to the laboratory, and then placed in cold storage at 5 °C until processing.

Laboratory analyses

Before analyses, whole samples were dried at 35 °C for 3–4 days and then ground by hand to pass a 2.0 mm sieve. Identifiable plant material ($>$2.0 mm) was removed during sieving. Laboratory analyses conducted on the soil samples included soil texture, soil pH, available P (North and South Dakota sites only), total carbon (C) and N, and inorganic C. Soil texture was determined using the hydrometer method with 40 g air-dried soil (Gee & Bauder, 1986). Soil pH was estimated from a 1 : 1 soil–water mixture (Watson & Brown, 1998). Plant available P was determined following the Olson method for calcareous soils (Kuo, 1996). Total soil C was determined by dry combustion on soil ground to pass a 0.106 mm sieve (Nelson & Sommers, 1996). Using the same fine-ground soil, inorganic C was measured on soils with a pH ≥ 7.2 by quantifying the amount of CO_2 produced using a volumetric calcimeter after application of dilute HCl stabilized with $FeCl_2$ (Loeppert & Suarez, 1996). Soil bulk density (SBD) was determined using the oven-dry weight and known volume of the composited samples (Blake & Hartge, 1986). SOC was calculated as the difference between total C and inorganic C. All data were expressed on an oven-dry basis. Initial soil attributes are presented in Table 2.

Data analyses

To eliminate effects of sampling depth and SBD on soil P and SOC, data from the initial and 5-year samplings were recalculated on an equivalent mass basis assuming soil profile masses of 2500 and 10 000 Mg ha^{-1} following the method of Ellert & Bettany (1995). The equivalent masses approximated soil within the 0–0.2 and 0–0.9 m depths, respectively.

Changes in soil properties between sampling times were calculated by subtracting initial values from values after 5 years (4 years for Atkinson) within a sampling location. Calculated changes were then evaluated within a site by depth using a paired *t*-test at $P \leq 0.1$ and 0.05 in PROC MIXED (Littel *et al*., 1996). Changes in soil properties for cumulative sampling depths (0–0.2 and 0–0.9 m) within and across sites were evaluated similarly. At locations with variable topography (Streeter, Bristol, Highmore, Crofton, Douglas, and Lawrence), soil properties were evaluated by landscape position. Only equivalent mass SOC during the 2001 sampling at the Streeter location exhibited a significant landscape effect (shoulder = 59.5 Mg C ha^{-1}, backslope = 58.5 Mg C ha^{-1}, footslope = 77.4 Mg C ha^{-1}; $P = 0.04$; data for other sites not shown). Given the modest effect of landscape position on soil properties, results were expressed across landscape position at each site. Associations between soil properties were identified using Pearson correlation analysis.

Results

Switchgrass affected changes in SBD, pH, soil P, and equivalent mass SOC at all sites (Tables 3 to 6). Based on the number of significant responses across sites and depths, available P was most affected by switchgrass (67% significant response), followed by SBD (50% significant response), SOC (40% significant response), and pH (20% significant response). Changes in soil properties occurred at all depths, but were most prevalent at 0–0.05 m. Conversely, the least number of significant responses to switchgrass occurred at the 0.1–0.2 m sample depth.

SBD changes were not consistent across sites (Table 3). Decreases in SBD tended to be more frequent in SD and ND than NE. Across sites, changes in SBD decreased in frequency with increased depth; the 0–0.05 m depth was most sensitive to changes in SBD (significant at eight sites), while the 0.3–0.6 m depth was least sensitive (significant at one site). Accordingly, changes in SBD were largely constrained to near-surface depths where the influence of plant biomass inputs, management, and freeze–thaw cycles are greatest. Tillage was conducted before sampling at Crofton and Douglas; two sites where SBD increased more than 0.2 Mg m^{-3} within the 0–0.05 m depth (Table 3). Overall, however, absolute changes in SBD were small (Table 3). Only at Huron, Ethan, Crofton, and Douglas did changes in SBD equal or exceed 0.2 Mg m^{-3} (all at 0–0.05 m).

Soil pH changed in response to switchgrass at eight of the 10 locations (six locations with $P < 0.05$) with the majority of changes occurring at the 0–0.05 m and 0.05–0.1 m depths (Table 4). Initial soil pH ranged from 5.64 (Douglas) to 8.02 (Munich) at 0–0.3 m depth. Numeri-

Table 2 Initial soil attribute mean values and corresponding standard errors by depth at each location established with switchgrass

Depth (m)	Soil bulk density ($\mathrm{Mg\,m^{-3}}$)	Soil pH ($-\log[\mathrm{H^+}]$)	Available P		Soil organic C		Sand ($\mathrm{g\,kg^{-1}}$)	Silt ($\mathrm{g\,kg^{-1}}$)	Clay ($\mathrm{g\,kg^{-1}}$)
			$\mathrm{mg\,P\,kg^{-1}}$	$\mathrm{kg\,P\,ha^{-1}}$	$\mathrm{g\,C\,kg^{-1}}$	$\mathrm{Mg\,C\,ha^{-1}}$			
Munich, ND									
0–0.05	1.33 (0.02)	7.76 (0.11)	26.5 (5.9)	17.6 (3.8)	27.2 (2.8)	18.0 (1.7)	369 (50)	373 (37)	258 (15)
0.05–0.1	1.38 (0.03)	7.90 (0.10)	7.6 (0.6)	5.4 (0.4)	24.3 (1.4)	16.7 (0.8)	378 (52)	359 (39)	263 (14)
0.1–0.2	1.32 (0.03)	8.08 (0.11)	5.2 (1.3)	6.7 (1.5)	17.3 (1.6)	22.8 (2.0)	328 (50)	378 (32)	294 (23)
0.2–0.3	1.25 (0.04)	8.35 (0.06)	2.6 (0.4)	3.2 (0.4)	17.3 (2.5)	22.1 (4.1)	316 (58)	379 (36)	305 (25)
Streeter, ND									
0–0.05	0.99 (0.02)	6.81 (0.39)	9.7 (0.4)	4.9 (0.1)	33.5 (2.3)	16.7 (0.8)	484 (43)	299 (22)	217 (24)
0.05–0.1	1.16 (0.03)	6.76 (0.38)	6.6 (0.7)	3.8 (0.4)	30.2 (2.3)	17.4 (1.0)	486 (42)	299 (22)	215 (23)
0.1–0.2	1.23 (0.05)	6.97 (0.34)	3.4 (0.5)	4.2 (0.6)	25.2 (2.3)	30.6 (2.2)	467 (50)	302 (23)	234 (29)
0.2–0.3	1.19 (0.06)	7.21 (0.33)	2.2 (0.3)	2.6 (0.4)	15.7 (2.7)	19.0 (2.5)	499 (72)	247 (28)	254 (49)
Bristol, SD									
0–0.05	1.09 (0.02)	7.62 (0.28)	7.3 (1.5)	4.0 (0.9)	28.6 (1.3)	15.5 (0.6)	375 (32)	358 (31)	267 (5)
0.05–0.1	1.23 (0.03)	7.60 (0.29)	3.0 (0.7)	1.9 (0.5)	24.5 (1.1)	15.1 (0.8)	375 (29)	356 (29)	269 (3)
0.1–0.2	1.22 (0.04)	7.59 (0.29)	2.1 (0.4)	2.7 (0.6)	21.3 (2.8)	25.7 (3.0)	354 (24)	360 (28)	286 (4)
0.2–0.3	1.24 (0.03)	7.77 (0.30)	2.6 (1.0)	3.3 (1.4)	15.6 (2.0)	19.1 (1.8)	341 (26)	363 (29)	296 (5)
Highmore, SD									
0–0.05	1.35 (0.05)	6.84 (0.35)	11.3 (1.8)	7.6 (1.2)	23.2 (1.3)	15.6 (0.9)	268 (35)	473 (27)	259 (12)
0.05–0.1	1.25 (0.04)	6.58 (0.41)	3.7 (0.5)	2.3 (0.2)	22.2 (1.6)	13.7 (0.5)	254 (40)	489 (33)	257 (12)
0.1–0.2	1.22 (0.02)	6.65 (0.46)	2.9 (0.4)	3.5 (0.5)	19.4 (1.5)	23.6 (1.5)	279 (30)	462 (19)	268 (15)
0.2–0.3	1.24 (0.04)	6.95 (0.42)	2.0 (0.3)	2.5 (0.4)	12.0 (1.3)	14.7 (1.4)	291 (29)	429 (13)	278 (20)
Huron, SD									
0–0.05	1.54 (0.04)	6.34 (0.27)	6.3 (0.5)	4.9 (0.4)	19.8 (0.7)	15.2 (0.5)	515 (38)	294 (24)	191 (15)
0.05–0.1	1.43 (0.04)	6.09 (0.27)	3.7 (0.4)	2.7 (0.2)	17.8 (0.9)	12.7 (0.8)	503 (38)	300 (24)	197 (15)
0.1–0.2	1.35 (0.02)	6.24 (0.28)	3.4 (0.4)	4.7 (0.6)	15.9 (0.8)	21.6 (0.9)	507 (49)	287 (28)	206 (24)
0.2–0.3	1.41 (0.02)	6.59 (0.26)	2.6 (0.5)	3.6 (0.7)	8.4 (1.0)	11.8 (1.3)	562 (65)	219 (26)	219 (45)
Ethan, SD									
0–0.05	1.34 (0.03)	5.62 (0.12)	10.7 (1.9)	7.0 (1.2)	18.9 (0.8)	12.5 (0.4)	320 (16)	415 (7)	265 (11)
0.05–0.1	1.42 (0.02)	5.81 (0.19)	3.3 (0.4)	2.3 (0.3)	15.9 (0.4)	11.2 (0.3)	303 (20)	425 (19)	272 (6)
0.1–0.2	1.32 (0.05)	6.29 (0.21)	1.4 (0.2)	1.9 (0.2)	13.4 (0.5)	17.7 (1.1)	352 (31)	362 (28)	286 (8)
0.2–0.3	1.23 (0.08)	6.88 (0.21)	1.1 (0.2)	1.4 (0.2)	9.1 (0.7)	11.0 (0.9)	382 (20)	331 (14)	287 (9)
Atkinson, NE									
0–0.05	1.31 (0.03)	6.23 (0.45)	–	–	11.9 (0.6)	7.8 (0.3)	888 (5)	69 (0)	43 (5)
0.05–0.1	1.47 (0.04)	5.66 (0.31)	–	–	8.1 (0.4)	5.9 (0.5)	891 (0)	62 (3)	47 (3)
0.1–0.2	1.61 (0.03)	5.38 (0.32)	–	–	7.1 (0.5)	11.3 (0.6)	873 (3)	77 (6)	50 (3)
0.2–0.3	1.63 (0.01)	5.42 (0.22)	–	–	5.8 (1.1)	9.4 (1.7)	876 (29)	70 (18)	54 (11)
Douglas, NE									
0–0.05	1.09 (0.04)	5.62 (0.16)	–	–	21.3 (1.2)	11.6 (0.7)	112 (53)	582 (30)	306 (28)
0.05–0.1	1.29 (0.04)	5.42 (0.10)	–	–	18.3 (1.1)	11.8 (0.7)	109 (54)	578 (33)	313 (28)
0.1–0.2	1.29 (0.04)	5.59 (0.06)	–	–	15.9 (1.0)	20.4 (1.1)	92 (42)	557 (31)	351 (24)
0.2–0.3	1.28 (0.04)	5.91 (0.06)	–	–	12.9 (1.2)	16.3 (1.3)	88 (45)	532 (35)	380 (24)
0.3–0.6	1.35 (0.03)	6.34 (0.08)	–	–	7.3 (0.9)	29.4 (3.2)	106 (60)	496 (47)	398 (22)
0.6–0.9	1.49 (0.05)	6.76 (0.13)	–	–	3.4 (0.3)	15.4 (1.4)	135 (84)	519 (69)	346 (21)
0.9–1.2	1.57 (0.05)	7.08 (0.22)	–	–	2.3 (0.4)	10.7 (1.8)	193 (104)	496 (85)	311 (25)
Crofton, NE									
0–0.05	0.97 (0.01)	8.07 (0.11)	–	–	18.7 (0.7)	9.0 (0.4)	104 (9)	601 (7)	295 (7)
0.05–0.1	1.16 (0.03)	7.79 (0.14)	–	–	16.4 (0.5)	9.5 (0.4)	105 (9)	579 (11)	316 (10)
0.1–0.2	1.29 (0.01)	7.82 (0.14)	–	–	13.3 (1.0)	17.0 (1.3)	100 (7)	585 (4)	315 (7)
0.2–0.3	1.24 (0.02)	7.80 (0.12)	–	–	8.9 (1.2)	10.9 (1.4)	95 (5)	605 (9)	300 (5)
0.3–0.6	1.23 (0.01)	7.96 (0.14)	–	–	7.1 (0.8)	26.2 (3.0)	93 (7)	621 (14)	286 (9)
0.6–0.9	1.29 (0.05)	8.16 (0.07)	–	–	6.5 (0.4)	25.4 (2.1)	90 (10)	629 (7)	281 (12)
0.9–1.2	1.32 (0.05)	8.25 (0.05)	–	–	5.7 (0.3)	22.4 (1.3)	101 (9)	638 (6)	261 (7)

Continued

Table 2 Continued

Depth (m)	Soil bulk density ($Mg\,m^{-3}$)	Soil pH ($-\log[H^+]$)	Available P		Soil organic C		Sand ($g\,kg^{-1}$)	Silt ($g\,kg^{-1}$)	Clay ($g\,kg^{-1}$)
			$mg\,P\,kg^{-1}$	$kg\,P\,ha^{-1}$	$g\,C\,kg^{-1}$	$Mg\,C\,ha^{-1}$			
Lawrence, NE									
0–0.05	1.21 (0.02)	5.60 (0.08)	–	–	12.7 (0.4)	7.7 (0.3)	67 (10)	628 (13)	305 (18)
0.05–0.1	1.34 (0.01)	5.50 (0.06)	–	–	10.9 (0.5)	7.3 (0.4)	67 (8)	612 (12)	321 (19)
0.1–0.2	1.37 (0.01)	6.02 (0.06)	–	–	7.3 (0.6)	10.0 (0.9)	69 (10)	596 (14)	335 (20)
0.2–0.3	1.40 (0.03)	6.60 (0.10)	–	–	4.1 (0.2)	5.7 (0.3)	67 (15)	571 (14)	362 (8)
0.3–0.6	1.39 (0.05)	7.16 (0.11)	–	–	2.6 (0.1)	10.8 (0.4)	73 (21)	575 (20)	352 (11)
0.6–0.9	1.33 (0.04)	7.66 (0.16)	–	–	1.9 (0.3)	7.5 (0.9)	75 (21)	612 (26)	313 (13)
0.9–1.2	1.35 (0.03)	7.84 (0.15)	–	–	1.9 (0.5)	7.5 (2.1)	79 (17)	628 (27)	293 (16)

Table 3 Change in soil bulk density at each site following 5 years under switchgrass

Location	ΔSoil bulk density ($Mg\,m^{-3}$) by depth (m)								
	0–0.05	0.05–0.1	0.1–0.2	0.2–0.3	0.3–0.6	0.6–0.9	0.9–1.2	0–0.3	0–1.2
Munich, ND	−0.17**	−0.04	0.00	0.07**	–	–	–	−0.01	–
Streeter, ND	−0.08**	−0.05	−0.05	−0.06	–	–	–	−0.06	–
Bristol, SD	0.07*	0.06	0.05	0.13**	–	–	–	0.08**	–
Highmore, SD	−0.30	−0.09	−0.06**	0.03	–	–	–	−0.07**	–
Huron, SD	−0.42**	−0.04	−0.06**	−0.01	–	–	–	−0.10**	–
Ethan, SD	−0.20**	−0.06	−0.06	0.05	–	–	–	−0.04	–
Atkinson, NE	0.14*	0.18	0.04	0.04	–	–	–	0.08	–
Douglas, NE	0.23**	0.10*	0.00	0.09	0.06	0.10**	0.03**	0.08	0.07*
Crofton, NE	0.25**	0.10**	0.03*	0.09**	0.14**	−0.01	−0.09**	0.10**	0.03**
Lawrence, NE	0.00	−0.01	0.07*	0.05	0.04	0.01	−0.02	0.04	0.01

*,**Change from initial sampling significant at $P \leq 0.1$ and 0.05, respectively.

Table 4 Change in soil pH at each site following 5 years under switchgrass.

Location	ΔSoil pH ($-\log[H^+]$) by depth (m)								
	0–0.05	0.05–0.1	0.1–0.2	0.2–0.3	0.3–0.6	0.6–0.9	0.9–1.2	0–0.3	0–1.2
Munich, ND	0.08	0.28**	0.04	0.21	–	–	–	0.14	–
Streeter, ND	−0.06	0.33*	0.24*	0.27	–	–	–	0.22**	–
Bristol, SD	−0.22	0.03	0.19	0.25	–	–	—	0.11	–
Highmore, SD	0.44**	0.46**	0.41**	0.45**	–	–	–	0.44**	–
Huron, SD	−0.24**	0.24**	0.18	0.15	–	–	–	0.11	–
Ethan, SD	0.32**	0.34**	0.20	0.24	–	–	–	0.26	–
Atkinson, NE	−0.16	0.17	0.06	0.02	–	–	–	0.03	–
Douglas, NE	−0.24**	−0.09	−0.08	−0.01	−0.16	−0.12	0.14	−0.08	−0.05
Crofton, NE	−0.67*	−0.26	−0.18	−0.08	−0.09	−0.20	−0.08	−0.24	−0.15
Lawrence, NE	−0.06	−0.03	−0.18	−0.36**	−0.33*	−0.03	−0.03	−0.19**	−0.22

*,** Change from initial sampling significant at $P \leq 0.1$ and 0.05, respectively.

cally, soil pH increased at all sites in ND and SD, but decreased at three out of four locations in NE (Table 4). Changes in soil pH at 0–0.3 m were significant at Streeter (increased), Highmore (increased) and Lawrence (decreased). Near-surface depths (above 0.1 m) were most sensitive to changes in pH, while no changes in pH were observed below 0.6 m. Only at Crofton did switchgrass production change pH more than half a unit (−0.67; 0–0.05 m), indicating absolute changes in pH across sites were relatively modest. Final soil pH ranged from 5.56 to 8.16 at a 0–0.3 m depth.

Plant available P declined at the North and South Dakota locations when expressed volumetrically and on an equivalent mass basis (Table 5). When summed across the surface 0.3 m depth, annual decreases in available P averaged 1.5 kg P ha^{-1} yr^{-1} (range = 0.5–2.8 kg P ha^{-1} yr^{-1}). Decreases in plant available P across locations ranged from 0.4 to 12.1 kg P ha^{-1} within the 2500 Mg ha^{-1} soil mass. Changes in plant available P expressed volumetrically and on an equivalent mass basis were strongly associated ($r = 0.99$; $P < 0.0001$). Conversely, changes in plant available P and aboveground biomass across years were not correlated ($P = 0.7453$).

Switchgrass production contributed to an increase in equivalent mass SOC for the 2500 Mg ha^{-1} and 10 000 Mg ha^{-1} soil masses when averaged across locations (Table 6). Equivalent mass SOC changes varied by location, however, with eight locations showing increased SOC and two locations showing decreased SOC at the 2500 Mg ha^{-1} soil mass (Table 6). The amount of variation in SOC change was not unexpected considering the regional scope of the study and the inherent soil variability found in on-farm field-scale conditions. The Nebraska locations that were sampled at soil profile depths of 1.2 m showed SOC increases averaging 1.4–3.3 Mg C ha^{-1} yr^{-1} using 10 000 Mg ha^{-1} soil mass. A significant SOC change ($P \leq 0.05$; 2.4 Mg C ha^{-1} yr^{-1}) was found for the 10 000 Mg ha^{-1} soil mass when averaged across the Nebraska locations (Table 6). Equivalent mass and volumetric SOC values were strongly associated based on correlation analyses. Correlation coefficients between SOC in the 2500 Mg ha^{-1} soil mass and volumetric SOC within the 0–0.3 m depth were 0.92 ($P < 0.0001$) for the initial sampling and 0.93 ($P < 0.0001$) for the 5-year sampling. Similarly, correlation coefficients for SOC in the 10 000 Mg ha^{-1} soil mass and volumetric SOC within the 0–1.2 m depth were 0.96 ($P < 0.0001$) for the initial sampling and 0.98 ($P < 0.0001$) for the 5-year sampling. Correlations between aboveground biomass across years and N rates with equivalent

Table 5 Change in plant available P expressed volumetrically and on an equivalent mass basis for six on-farm locations in North and South Dakota following 5 years of switchgrass production

	Location					
Depth (m)	Munich, ND	Streeter, ND	Bristol, SD	Highmore, SD	Huron, SD	Ethan, SD
ΔP, volumetric (kg P ha^{-1})						
0–0.05	−9.3	−3.5**	−2.2**	−1.4	−2.7**	−2.4
0.05–0.1	−0.6	−2.6**	−0.8	0.1	−1.1**	0.1
0.1–0.2	−2.9	−2.9**	−1.5**	0.0	−2.8**	−0.5
0.2–0.3	−1.4	−1.9**	−2.4	−1.2*	−1.8**	−1.0**
0–0.3	−14.2*	−10.9**	−6.9*	−2.5	−8.4**	−3.8
ΔP, 2500 Mg soil ha^{-1} (kg P ha^{-1})						
	−12.1*	−9.6**	−4.5**	−0.4	−5.5**	−2.3

*,** Change from initial sampling significant at $P \leq 0.1$ and 0.05, respectively.

Table 6 Soil organic C stocks for two soil masses (2500 and 10 000 Mg ha^{-1}) at the initial and 5-year samplings under switchgrass

	2500 Mg soil ha^{-1}			10 000 Mg soil ha^{-1}		
Location	Initial (Mg C ha^{-1})	5-year (Mg C ha^{-1})	ΔSOC (Mg C ha^{-1})	Initial (Mg C ha^{-1})	5-year (Mg C ha^{-1})	ΔSOC (Mg C ha^{-1})
Munich, ND	57.1 (3.7)†	64.2 (5.9)	7.1*	–	–	–
Streeter, ND	65.1 (4.0)	65.7 (3.8)	0.6	–	–	–
Bristol, SD	56.5 (3.4)	64.9 (3.5)	8.4*	–	–	–
Highmore, SD	52.8 (2.4)	54.8 (4.1)	2.0	–	–	–
Huron, SD	49.0 (1.6)	43.4 (1.1)	−5.6**	–	–	–
Ethan, SD	41.1 (1.0)	38.2 (1.4)	−2.9	–	–	–
Atkinson, NE	44.3 (1.6)	46.9 (0.1)	2.6	–	–	–
Douglas, NE	43.8 (2.2)	47.6 (4.1)	3.8	104.1 (7.2)	120.5 (15.1)	16.4
Crofton, NE	35.7 (2.0)	37.4 (1.0)	1.7	97.3 (6.8)	104.1 (10.8)	6.8
Lawrence, NE	24.9 (1.3)	27.9 (2.0)	3.0	48.5 (2.0)	61.7 (3.8)	13.2**
Across locations	47.0 (3.7)	49.4 (4.1)	2.4	83.3 (17.5)	95.4 (17.5)	12.1**

*,** Change from initial sampling significant at $P \leq 0.1$ and 0.05, respectively.

†Values in parentheses represent standard error of the mean.

mass SOC changes were $P = 0.2218$ and $P = 0.1644$, respectively.

Discussion

Potential improvements in near-surface soil function are particularly important should switchgrass be included as a perennial phase in cropping systems, as these attributes would be expected to enhance crop productivity following the transition to annual cropping (Entz *et al.*, 2002). Switchgrass tends to reduce SBD more than annual row crops or perennial, cool-season grasses (Murphy *et al.*, 2004; Rachman *et al.*, 2004). Decreases in SBD in near-surface depths from this study were likely attributed to increased root biomass in the surface volume of soil (Table 3). Frank *et al.* (2004) found root biomass of switchgrass in the surface 0.3 m to account for nearly 50% of total root biomass over a 1.1 m soil depth. Increases in SBD under switchgrass at the Nebraska locations were likely caused by tillage operations immediately before soil sampling, which would have acted to decrease initial SBD considerably for soils with a silty clay loam texture (Tables 2 and 3). Near-surface SBD at the Nebraska locations would be expected to increase with subsequent reconsolidation (Pikul *et al.*, 2006). Overwinter changes in soil structural attributes from freeze–thaw cycles may also contribute to lower SBD in near-surface depths (Perfect *et al.*, 1990), though investigations on this topic are scarce. Initial soil pH at all locations did not inhibit switchgrass establishment based on switchgrass's ability to germinate and grow under variable pH ranges (Hanson & Johnson, 2005; Parrish & Fike, 2005). Soil pH changes, when significant, were modest suggesting minimal impact on subsequent cropping systems (Table 4).

Switchgrass grown in higher precipitation regions have P removal rates between 7 and 14 $\mathrm{kg\,P\,ha^{-1}\,yr^{-1}}$ (Heggenstaller *et al.*, 2009; Lemus *et al.*, 2009). Harvest timing can influence P removal rates with aboveground P concentrations differing by harvest dates (Adler *et al.*, 2006; Dien *et al.*, 2006). P mobilization from the shoots to the roots is less than N shoot to root mobilization for upland ecotypes (Heggenstaller *et al.*, 2009). Plant available P unlikely reached a critical threshold in this study to negatively impact biomass yields (Tables 2 and 5). Previous research has shown application rates of 10–40 $\mathrm{kg\,P\,ha^{-1}}$ did not affect switchgrass yield for upland or lowland ecotypes (Jung *et al.*, 1988; Muir *et al.*, 2001). Switchgrass forms strong associations with mycorrhizal fungi, which increases P uptake under low P levels limiting the need for supplemental P (Brejda *et al.*, 1993). However, switchgrass managed for biomass >5 years may require supplemental P to ensure long-term yield stability.

Switchgrass has an extensive, fibrous root system that extends 3 m below the soil surface, making it a good candidate to sequester C (Weaver & Darland; 1949). Soil organic C increased at rates ranging from 1.7 to 10.1 $\mathrm{Mg\,C\,ha^{-1}\,yr^{-1}}$ after switchgrass establishment throughout North America (Garten & Wullschleger, 2000; Zan *et al.*, 2001; Frank *et al.*, 2004; Lee *et al.*, 2007). Results from this study showed similar SOC accrual rates albeit with limited statistical significance given the inherent site-by-site variation characteristic of on-farm conditions coupled with the relatively short timeframe of the investigation. Considerable SOC gains for switchgrass have been reported below 0.3 m depths (Frank *et al.*, 2004; Liebig *et al.*, 2005; Lee *et al.*, 2007). Similar findings from this study showed SOC gains at depth for the Nebraska sites when expressed on an equivalent mass basis (Table 6). Depth distribution of increased SOC has relevance to soil function, as near-surface increases in SOC influence nutrient conservation, water infiltration, and erosion control (Franzluebbers, 2002). Increasing SOC, below the microbially active surface horizon acts to enhance the role of soil as a repository for organic matter as mineralization and loss of C decreases with increasing depth (Grigal & Berguson, 1998; Blanco-Canqui, 2010). Equivalent mass SOC trends were similar to volumetric SOC trends reported earlier (Liebig *et al.*, 2008). Equivalent mass SOC mean values were smaller in relation to volumetric SOC changes, a result of using the shallower sampling depth to account for variation in SBD (Ellert & Bettany, 1995).

Fertilizer additions to grassland systems have shown to increase SOC and root C storage but overall changes varies by soil type and climate (Conant *et al.*, 2001; Ma *et al.*, 2001; Lee *et al.*, 2007; Heggenstaller *et al.*, 2009; Blanco-Canqui, 2010). N fertilizer recommendation rates for this study were based on expected yield for each location which varied depending on climate (Vogel *et al.*, 2002). Results from this study did not show a significant relationship between SOC changes and management practices (N fertilizer rates) or environmental conditions (i.e. precipitation, temperature) when evaluated across locations (data not shown).

Reconstructed prairies have shown SOC differences by landscape positions and by sample period for shallow sampling depths (0–0.15 m) (Guzman & Al-Kaisi, 2010). Soil property changes were analyzed by landscape features in this study but were largely insignificant with only the Streeter location showing differences in SOC by landscape position during the initial sampling. Switchgrass aboveground biomass yields have shown little variation when evaluated across landscape features in the Central US (Lee *et al.*, 2009; Schmer *et al.*, 2010; Thelemann *et al.*, 2010). Soil parameters of N, pH, P, and soil moisture explained more of the switchgrass yield variation than topographic effects on a switchgrass field in Europe (Di Virgilio *et al*., 2007).

Regional trials provide useful insights regarding the contribution of switchgrass to affect soil properties, and how such affects may impact subsequent cropping systems. In this study, soil property changes of SBD, pH, and available P were largely confined to shallow depths under switchgrass managed for bioenergy. Absolute changes in SBD, pH, and available P were relatively small. These changes to these properties would be expected to have minimal impact on subsequent annual cropping systems since most crops grown in the Great Plains have a wide range of suitable soil conditions for growth. Changes in equivalent mass SOC corresponded to previous estimates of volumetric SOC dynamics. Across locations, equivalent mass SOC under switchgrass increased by $2.4\,\mathrm{Mg\,C\,ha^{-1}\,yr^{-1}}$ for the $10\,000\,\mathrm{Mg\,ha^{-1}}$ soil mass. Further quantification of long-term trends (>5 years) in soil properties will be critical to ensure switchgrass yield stability and subsequent annual row crop success. These results demonstrate that switchgrass from a soils aspect should be a sustainable energy crop for the Northern and Central Great Plains and adjacent Midwest states because of its role in soil C sequestration throughout the soil profile and its minimal impact on other important soil properties.

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