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Soil Carbon Storage by Switchgrass Grown for Bioenergy

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Abstract Life-cycle assessments (LCAs) of switchgrass (*Panicum virgatum* L.) grown for bioenergy production require data on soil organic carbon (SOC) change and harvested C yields to accurately estimate net greenhouse gas (GHG) emissions. To date, nearly all information on SOC change under switchgrass has been based on modeled assumptions or small plot research, both of which do not take into account spatial variability within or across sites for an agro-ecoregion. To address this need, we measured change in SOC and harvested C yield for switchgrass fields on ten farms in the central and northern Great Plains, USA (930 km latitudinal range). Change in SOC was determined by collecting multiple soil samples in transects across the fields prior to planting switchgrass and again 5 years later after switchgrass had been grown and managed as a bioenergy crop. Harvested aboveground C averaged 2.5± 0.7 Mg C ha^{-1} over the 5 year study. Across sites, SOC increased significantly at 0–30 cm (P=0.03) and 0–120 cm (P=0.07), with accrual rates of 1.1 and 2.9 Mg C ha^{-1} $year^{-1}$ (4.0 and 10.6 Mg CO_2 ha^{-1} $year^{-1}$), respectively. Change in SOC across sites varied considerably, however, ranging from −0.6 to 4.3 Mg C ha^{-1} $year^{-1}$ for the 0–30 cm depth. Such variation in SOC change must be taken into consideration in LCAs. Net GHG emissions from bioenergy crops vary in space and time. Such variation, coupled with an increased reliance on agriculture for energy production, underscores the need for long-term environmental monitoring sites in major agro-ecoregions.

Keywords Bioenergy · Carbon sequestration · Greenhouse gas balance · Perennial biofeedstocks · Switchgrass

Abbreviations

GHG	Greenhouse gas
LCAs	Life-cycle assessments
SOC	Soil organic carbon

Introduction

Environmental and social consequences associated with large-scale biofuel production from grain, sugar, and dedicated bioenergy crops are being critically examined [16, 30, 36]. Utilization of perennial herbaceous crops as biofuel sources has been purported to mitigate negative consequences due mainly to their lower requirements of fertilizers and pesticides relative to annual crops and their ability to be grown on marginal land [16, 36]. Among the portfolio of herbaceous perennial crops considered for adoption throughout the USA, switchgrass (*Panicum virgatum* L.) has shown promise as a cellulosic ethanol source due to its high productivity across a large geographical domain [26]. Results from life-cycle assessments (LCAs) of switchgrass grown for bioenergy, however, have been mixed [1, 8, 32, 33], due in large part to the assigned net GHG emissions associated with switchgrass production and assumptions made in indirect land conversion costs.

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Net GHG emissions from switchgrass bioenergy production are inextricably linked to carbon dioxide uptake and subsequent sequestration in soil. Carbon sequestration by switchgrass has been nearly ubiquitous across a broad range of growing conditions throughout North America at rates of 1.7–10.1 Mg C ha^{-1} $year^{-1}$ (6.2–37.0 Mg CO_2 ha^{-1} $year^{-1}$) [11, 13, 18, 45]. Nearly all measurements of soil organic carbon (SOC) change under switchgrass have been based on small plot research. While these assessments are useful, small plot research does not take into account spatial variability within or across farmer-managed fields. Furthermore, extension of results from small plot research to an agro-ecoregion is, at best, tenuous.

To obtain relevant, field-scale information for an agro-ecoregion, we sought to determine SOC change and harvested C yield within switchgrass fields on ten farms in the central and northern Great Plains, USA. Farms were located in Nebraska, South Dakota, and North Dakota, encompassing an area where previous modeling efforts have shown switchgrass production for bioenergy to be economically feasible [40]. Switchgrass fields included in the study were the focus of previously published net energy and economics analyses [29, 32].

Methods

Experimental Sites

Sites included in the study extended 930 km north to south and 230 km east to west within the Great Plains states of Nebraska, South Dakota, and North Dakota (Fig. 1). Major Land Resource Areas (MLRA) representative of study sites encompassed approximately 30 Mha and included 53B and C (Central and Southern Dark Brown Glaciated Plains), 55A, B, and C (Northern, Central, and Southern Black Glaciated Plains), 65 (Nebraska Sand Hills), 75 (Central Loess Plains), 102C (Loess Uplands), and 106 (Nebraska and Kansas Loess Drift Hills) [3]. Climate within the region is generally classified as semiarid to subhumid continental, with cold and dry winters, warm to hot summers, and erratic precipitation [3]. Mean annual precipitation for the study sites ranges from 432 to 777 mm increasing from west to east, while mean annual temperature ranges from 4.7°C in the north to 10.6°C in the south. Soils at the sites possessed high inherent fertility, with Ustolls and Udolls as the dominant taxonomic suborders [38] (Table 1).

Initial soil conditions at the ten sites were not limiting to switchgrass establishment and growth [see supplementary online material]. Medium textured soils were prevalent across the sites, with the exception of the soil at Atkinson, which was classified as sand. Values for soil bulk density across sites were below critical threshold values for restriction of root growth [17]. Soil pH across sites varied from strongly acid to moderately alkaline [37] (data not shown), and fell within a range for successful switchgrass germination [15].

Sites seeded to switchgrass were fields on working farms previously used for annual crop production. Field characteristics were such that they would have qualified for enrollment in the Conservation Reserve Program (CRP) [31]. Field size across sites averaged 6.7 ha (Range=3.0 to 9.5 ha). Sites at Douglas, Lawrence, and Crofton were seeded to switchgrass in 2000, while all other sites were seeded in 2001. Cultivars used for seeding included Cave-in-Rock (Douglas, Lawrence), Trailblazer (Douglas, Lawrence, Crofton, Atkinson, Huron, Highmore, Bristol), Shawnee (Lawrence, Crofton, Ethan), and Sunburst (Streeter, Munich). With the exception of Sunburst, all cultivars originated south of 43°N latitude [4]. Switchgrass was seeded at a rate of 322 pure live seeds (PLS) m^{-2}, or approximately 10 kg ha^{-1} using minimum or no-till management practices. Application of N varied in amount and type across sites based on biomass yield expectations and soil moisture conditions. Over the 5 year period of the switchgrass stands, site averages of applied N ranged from 31 to 104 kg N ha^{-1} $year^{-1}$ (Mean=74 kg N ha^{-1}). With the exception of the establishment year, aboveground biomass was harvested annually and baled. Most cooperating farmers harvested at emerged inflorescence to post-anthesis (early to mid-August) in post-establishment years. In contrast, farmers at Bristol, SD and Munich, ND harvested after a killing frost [32]. Biomass samples from switchgrass bales were used to determine dry matter and C concentration. Harvested C was determined by multiplying the biomass yield by the biomass C concentration. To verify machine harvested yields, aboveground biomass was hand-clipped, dried, and weighed from 1.1 m^2 quadrants at 16 locations within each field [32]. Additional details on site establishment, management, and biomass harvest and analysis are outlined elsewhere [31, 32].

Sampling Protocol

To evaluate change in SOC under switchgrass over time, soil samples were collected from each site on a 5 year time-step. Sites in Nebraska were sampled in 2000 and 2005, while all other sites were sampled in 2001 and 2006. 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 prior to switchgrass planting.

At each site, soil samples were collected from two transects with three sampling locations each (located approximately 30 m apart), resulting in a total of six sampling locations per site. Coordinates for each sampling location were recorded using a handheld GPS devise with an accuracy of <3 m (Garmin International, Inc., Olathe, KS). Sampling locations were treated as pseudoreplicates as reviewed by Gomez [14].

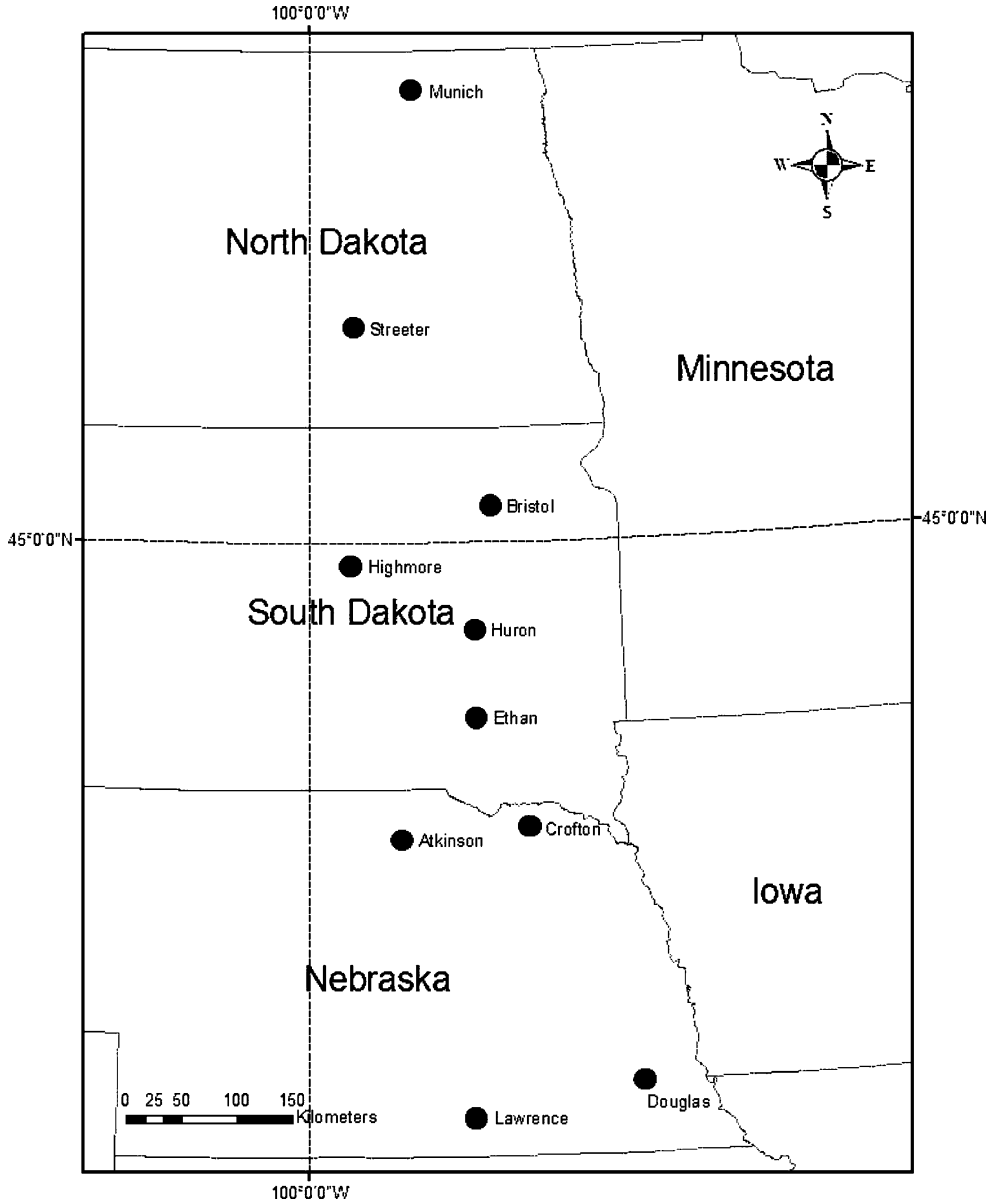

Fig. 1 Sampling sites for evaluating change in soil organic carbon under switchgrass

Due to difficulty during initial sample collection at Atkinson, only two locations per transect were sampled.

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 0–5, 5–10, 10–20, 20–30, 30–60, 60–90, and 90–120 cm for three Nebraska sites (Crofton, Douglas, Lawrence) and 0–5, 5–10, 10–20, and 20–30 cm for the remaining sites. To ensure adequate sample mass for laboratory analyses, seven soil cores were composited at each sampling location (approximately 1 m^2) for the 0–5 and 5–10 cm depths, five soil cores for the 10–20 and 20–30 cm depths, and two soil cores for the 30–60, 60–90, and 90–120 cm 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

Prior to analyses, whole soil samples were dried at 35°C for 3 to 4 days and then ground by hand to pass a 2.0 mm sieve. Identifiable plant material (>2.0 mm in diameter, >10 mm in length) was removed during sieving. Total soil C was determined by dry combustion on soil ground to pass a 0.106 mm sieve using a Carlo Erba NA 1500 CN analyzer (Thermo Scientific, Waltham, MA, USA). 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 $FeCl_2$ [24]. Soil organic C was calculated as the difference

Table 1 Location, climate, and soil attributes for sites included in study (listed by decreasing latitude)

Site	MAP (mm)	MAT (°C)	Prevalent soil type	Soil classification
Munich, ND	460	4.7	Barnes–Buse loams, 3% to 6% slopes	Fine-Loamy, Mixed, Superactive, Frigid Calcic Hapludolls and Argiudolls
Streeter, ND	432	5.5	Barnes–Svea loams, 0% to 6% slopes	Fine-loamy, Mixed, Superactive, Frigid Calcic and Pachic Hapludolls
Bristol, SD	559	5.6	Forman–Buse–Aastad loams, 2% to 9% slopes	Fine-Loamy, Mixed, Superactive, Frigid Calcic and Pachic Argiudolls
Highmore, SD	538	8.7	Glenham–Prosper loams, 2% to 6% slopes	Mixed, Superactive, Mesic Typic and Pachic Argiustolls
Huron, SD	531	7.5	Houdek–Prosper loams, 2% to 6% slopes	Fine-Loamy, Mixed, Superactive, Mesic Typic and Pachic Argiustolls
Ethan, SD	577	9.1	Houdek–Prosper loams, 0% to 2% slopes	Fine-Loamy, Mixed, Superactive, Mesic Typic and Pachic Argiustolls
Crofton, NE	704	9.3	Crofton–Nora complex, 6% to 11%-slopes, eroded	Fine-Silty, Mixed, Superactive, Calcareous, Mesic Udic Ustorthents and Fine-Silty, Mixed, Superactive, Mesic Udic Haplustolls
Atkinson, NE	625	9.1	Dunn loamy sand, 0% to 3% slopes	Sandy Over Loamy, Mixed, Superactive, Mesic Oxyaquic Haplustolls
Douglas, NE	777	10.6	Wymore silty clay, 2% to 7% slopes, eroded	Fine, Smectitic, Mesic Aquertic Argiudolls
Lawrence, NE	668	10.0	Hastings silt loam, 1% to 3% slopes	Fine, Smectitic, Mesic Udic Argiustolls

MAP mean annual precipitation, *MAT* mean annual temperature

between total C and inorganic C. Gravimetric data were converted to a volumetric basis for each sampling depth using field measured soil bulk density, which was determined using the oven-dry weight and known volume of the composited samples [5]. All data were expressed on an oven-dry basis.

Biomass samples were ground to pass a 1 mm screen prior to C determination by near infrared spectrophotometry (NIRS) [34]. A switchgrass NIRS prediction equation was based on total C analyses of a set of 108 switchgrass samples using combustion analysis [41]. The NIRS standard error of calibration and prediction for biomass C were 2.13 and 3.95 g kg^{-1}, respectively.

Statistical Analyses

Changes in SOC between sampling times were calculated by subtracting initial values from values after 5 years within a sampling location. Calculated changes were then evaluated within a site by depth using a paired *t*-test in PROC MIXED [22]. Changes in SOC over time for cumulative sampling depths (0–30 and 0–120 cm) within and across sites were evaluated similarly.

Results

Soil organic C changed in response to switchgrass biomass production at all sites within a 5 year period (Table 2). Soil organic C generally increased across sites; only at Huron and Ethan were significant SOC decreases observed. Soil bulk density decreased significantly in near-surface depths at Huron and Ethan, contributing to decreased SOC. Changes in SOC across sites were most prevalent at 0–5 and 20–30 cm. No significant changes in SOC were observed at 10–20 cm. Of the 52 site-depths evaluated, increases in SOC over 5 years exceeded 2 Mg C ha^{-1} in 18 site-depths, while increases >5 Mg C ha^{-1} were observed in six site-depths. Gravimetric and volumetric expressions of changes in SOC were correlated (r=0.55; P<0.01), as were changes in SOC (volumetric) and soil bulk density (r=0.51; P<0.01).

Sites at Streeter, Highmore, Atkinson, and Lawrence exhibited significant increases in SOC when summed over the 30 or 120 cm sampling depths (Fig. 2). Soil organic C accrual rates for responsive sites ranged from 0.8–1.2 Mg C ha^{-1} year^{-1} for the 0–30 cm depth. The only site with a significant increase in SOC over the 120 cm sampling depth was Lawrence, with an accrual rate of 3.8 Mg C ha^{-1} year^{-1}. Across sites, SOC increased significantly at 0–30 cm (P=0.03) and 0–120 cm (P=0.07) (Fig. 2). Rates of SOC accrual across sites were 1.1 and 2.9 Mg C ha^{-1} year^{-1} for the 0–30 and 0–120 cm depths, respectively. No significant associations were observed between annual change in SOC at 0–30 cm and relevant edaphic and climatic attributes (data not shown).

Harvested aboveground C averaged 2.5±0.7 Mg C ha^{-1} over a 5 year period across all ten farms (Figs. 2 and 3). Increased biomass yields contributed to greater harvested aboveground C over time, which peaked in the

Table 2 Change in soil bulk density and soil organic C at each site after 5 years under switchgrass

Site	Soil depth (cm)						
	0–5	5–10	10–20	20–30	30–60	60–90	90–120
	Soil bulk density (Mg m^{-3})						
Munich, ND	−0.17**	−0.04	0.00	0.07**	–	–	–
Streeter, ND	−0.08**	−0.05	−0.05	−0.06	–	–	–
Bristol, SD	0.07*	0.06	0.05	0.13**	–	–	–
Highmore, SD	−0.30	−0.09	−0.06**	0.03	–	–	–
Huron, SD	−0.42**	−0.04	−0.06**	−0.01	–	–	–
Ethan, SD	−0.20**	−0.06	−0.06	0.05	–	–	–
Crofton, NE	0.25**	0.10**	0.03*	0.09**	0.14**	−0.01	−0.09*
Atkinson, NE	0.14*	0.18	0.04	0.04	–	–	–
Douglas, NE	0.23**	0.10*	0.00	0.09	0.06	0.10**	0.03*
Lawrence, NE	0.00	−0.01	0.07*	0.05	0.04	0.01	−0.02
	Soil organic C (g C kg^{-1})						
Munich, ND	4.7	2.6*	4.3	0.8	–	–	–
Streeter, ND	1.8	1.4	1.9	5.4**	–	–	–
Bristol, SD	2.6*	2.3	2.0	6.7	–	–	–
Highmore, SD	7.8**	0.3	2.5	3.8**	–	–	–
Huron, SD	−2.1	−0.9	0.9	2.4	–	–	–
Ethan, SD	1.9**	−1.2**	−0.4	−0.4	–	–	–
Crofton, NE	0.0	−1.1	−0.7	0.6	0.8	−0.6	0.1
Atkinson, NE	0.0	1.8	1.1	0.3	–	–	–
Douglas, NE	1.1	−0.2	−0.3	−0.1	0.8	1.3	0.3
Lawrence, NE	2.1	0.5	0.7	1.0**	0.8**	1.3**	1.4**
	Soil organic C (Mg C ha^{-1})						
Munich, ND	0.31	1.19	5.37	1.51	–	–	–
Streeter, ND	−0.54	−0.10	0.83	4.01**	–	–	–
Bristol, SD	2.52*	2.21*	3.97	12.97	–	–	–
Highmore, SD	0.55	−0.76	1.69	5.23**	–	–	–
Huron, SD	−5.28**	−1.06	0.35	3.32	–	–	–
Ethan, SD	−0.75	−1.23**	−1.29	0.05	–	–	–
Crofton, NE	2.32**	0.16	−0.51	1.70*	6.19	−2.77	−0.79
Atkinson, NE	0.77	2.20**	2.01	0.74	–	–	–
Douglas, NE	3.38**	0.82	−0.25	1.19	5.04	6.71	1.51
Lawrence, NE	1.32	0.28	1.53	1.55**	3.62**	5.24**	5.29

*$P \leq 0.1$ (change from initial sampling significant); **$P \leq 0.05$ (change from initial sampling significant)

fourth year at 3.7±0.8 Mg C ha^{-1} (Fig. 3). Variation in harvested C was largely due to variation in biomass yield, as variation in biomass C concentration was limited (Biomass C_{Mean}=444.1±6.1 g C kg^{-1}, Biomass C_{Range}=425–454 g C kg^{-1}). Weather conditions as well as deviations from recommended management practices contributed to variation in biomass yield across sites [32]. Full biomass yield potential of switchgrass often is not achieved until one to two growing seasons following establishment. However, once mature, switchgrass stands have been shown to produce consistent biomass yields over time [9]. Harvested aboveground C was positively correlated with annual change in SOC at 0–30 cm, though the relationship was weak (Harvested C_{Mean}, r=0.50; P=0.14). Annual change in SOC was more strongly associated with mean and maximum aboveground biomass hand-clipped from quadrants located throughout each field ($Yield_{Mean}$, r=0.68, P<0.05; $Yield_{Max}$, r=0.77, P<0.01).

Discussion

The capacity of perennial grasses to affect change in soil properties over time is well documented [10], but information specific to switchgrass managed for bioenergy production is limited. In this study, switchgrass significantly affected change in SOC, a parameter known to respond slowly to changes in management in semiarid agro-ecosystems [27]. In addition to the relatively rapid response, change in SOC was detected on working farms, where spatial variation and potential measurement errors can increase the minimum detectable change in SOC over time.

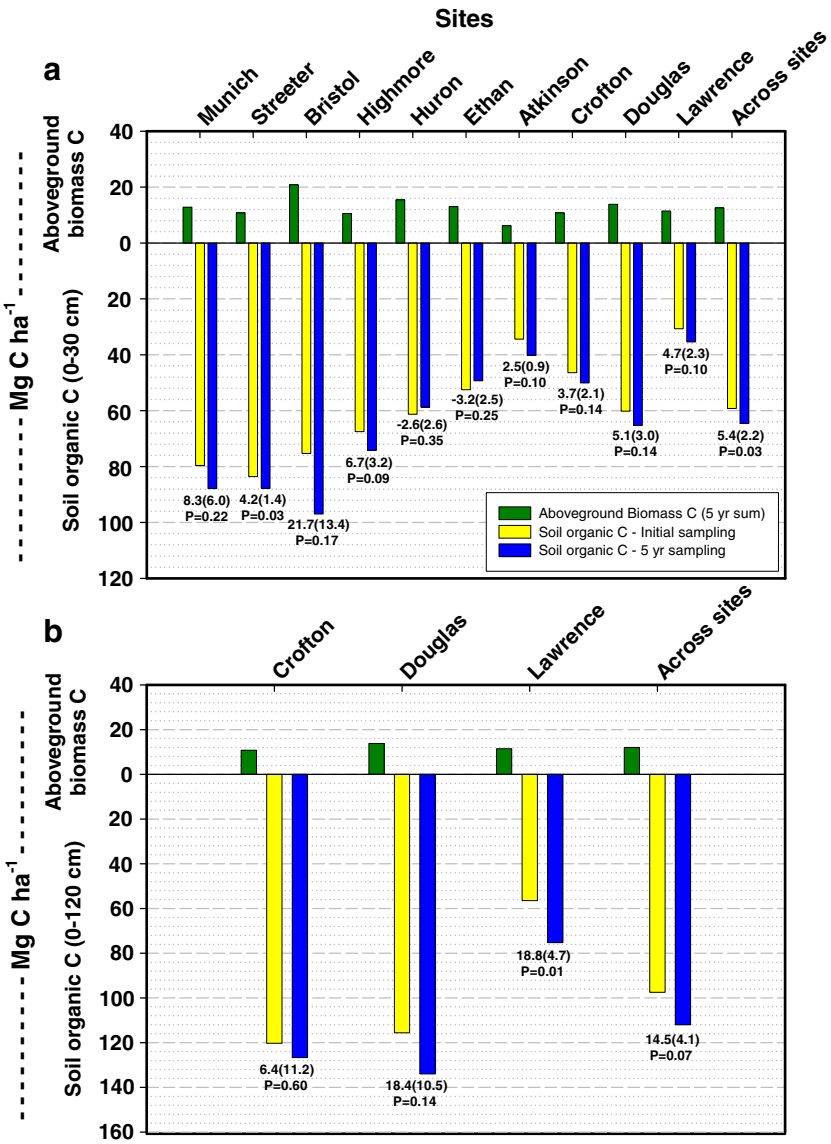

Fig. 2 Aboveground biomass C and change in soil organic C (SOC) over 5 years at 0–30 and 0–120 cm for sites included in study. **a** Results within and across ten sites sampled to 0–30 cm depth. Results from Atkinson site based on 4 year switchgrass stand. **b** Results within and across three sites sampled to 120 cm depth. Change in SOC ± 1 standard error along with the *P*-value for change in SOC over time is provided within and across sites

Increases in SOC under switchgrass were likely caused by belowground C input from root biomass and rhizodeposition [11, 45] and decreased soil organic matter losses by erosion [6]. Research conducted by ecologist John Weaver and his graduate students over 60 year ago provide ancillary support for increased SOC under switchgrass [35, 42, 43]. Their detailed surveys of prairie grass roots indicated switchgrass to have the deepest root system of all grasses examined, with roots extending to a soil depth of 3 m [42]. This finding, coupled with observations that prairie grass roots regenerate by replacing dying roots with new, live roots [43] indicates the potential for significant C input to the soil under switchgrass.

Depth distribution of increased SOC has relevance to nutrient conservation, water infiltration, and erosion control [12]. Potential improvements in near-surface soil functions resulting from increased SOC are particularly important

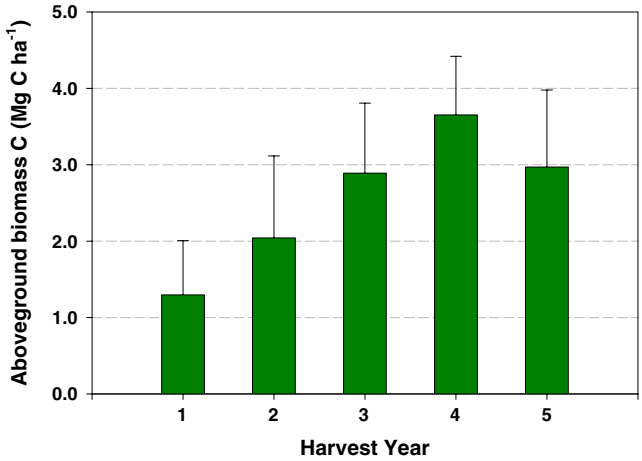

Fig. 3 Aboveground biomass C across sites for each year of study, ± 1 standard error

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 [7]. Accordingly, increases in SOC below the microbially-active surface horizon act to enhance the role of soil as a repository for atmospheric C, as mineralization and loss of C decreases with increasing depth. Increased SOC under switchgrass at depths below 30 cm is common, having been observed in other studies in the northern Great Plains [11, 18, 20]. In contrast to the assumptions made recently [33], it is likely much of the carbon sequestered during switchgrass production would be conserved because plowing is no longer necessary to rotate from pasture grasses to grain crops and back again because of advances in no-till technology. The same technology can be applied to switchgrass grown for bioenergy [28].

Accrual rates of SOC under switchgrass contribute significantly to its potential to provide a favorable net GHG balance [8, 32]. Though inclusive GHG flux field assessments of switchgrass are lacking, SOC accrual rates under switchgrass appear—in this, and other related studies [18]—large enough to easily offset nitrous oxide (N_2O) emissions. Greenhouse gas flux measurements from fertilized perennial grasses support this notion. Annual N_2O emission from a crested wheatgrass pasture fertilized with synthetic N was found to be 3.4 kg N ha^{-1} $year^{-1}$ [19], equating to 1.6 Mg CO_2e ha^{-1} $year^{-1}$, or approximately 40% of the C sequestration rate at 0–30 cm observed across sites in this study. Methane (CH_4) flux contributions to net GHG emission from switchgrass would likely be negligible, as perennial grasses in semiarid regions are a minor sink for atmospheric CH_4 [21]. Field-based assessments of both N_2O and CH_4 flux are urgently needed to assign greater confidence to estimates of net GHG emission for switchgrass.

U.S. federal law [39] will require renewable biofuels to meet certain GHG emission reductions from conventional gasoline using LCAs. Accordingly, data generated in this study should prove useful for scientists and policy makers conducting and/or using LCAs of bioenergy production systems. Previous LCAs including switchgrass production for biomass energy have utilized C offset rates four- to 11-fold lower than the C sequestration rates observed in this study [1, 32, 33]. It is important to acknowledge, however, LCAs have included GHG emissions associated with fertilizer and machinery use (e.g., GREET-derived C offset) [44], which would act to decrease net C offsets. Furthermore, LCAs generally calculate C sequestration over 30 or 100 year time periods, during which time the soil C accrual rate would be expected to plateau [2].

Results from this study underscore the importance of LCAs to account for inter- and intra-site variability inherent to key input parameters such as SOC. Variability in SOC change across sites within the studied agro-ecoregion was significant, from −0.6 to 4.3 Mg C ha^{-1} $year^{-1}$ for the 0–30 cm depth. Similar variation would likely exist in other agro-ecoregions. Accordingly, LCAs should acknowledge this variability by including confidence intervals in addition to means for estimating the effects of agricultural production practices on the environment.

Research conducted on working farms can provide critical information regarding agroecosystem effects on agronomic and environmental performance under conditions not available at research stations [23]. Placement of studies on working farms, however, has drawbacks. As an example, farmers in this study participated via a 5 year contract. It was not feasible to extend the contract for an array of reasons that differed with each farmer. Yet measurement of SOC change under switchgrass beyond 5 year represents a critical research need in order to quantify GHG balance over the long-term. Such a situation highlights the need for an expansion of the Long Term Ecological Research (LTER) Network to sites devoted to evaluation of agricultural production systems [25]. Agriculture is now being asked to supply food, feed, fiber, and energy for a growing population. Because of the potentially large positive or negative effects associated with the added requirements of energy production within agro-ecosystems, expansion of Agricultural LTER sites in major agro-ecoregions needs to be seriously considered for monitoring environmental effects over the long-term.

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