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Nitrogen and harvest effects on soil properties under rainfed switchgrass and no-till corn over 9 years: implications for soil quality

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Abstract

Nitrogen fertilizer and harvest management will alter soils under bioenergy crop production and the long-term effects of harvest timing and residue removal remain relatively unknown. Compared to no-tilled corn (NT-C, Zea mays L.), switchgrass (Panicum virgatum L.) is predicted to improve soil properties [i.e. soil organic C (SOC), soil microbial biomass (SMB-C), and soil aggregation] due to its perennial nature and deep-rooted growth form, but few explicit field comparisons exist. We assessed soil properties over 9 years for a rainfed study of N fertilizer rate (0, 60, 120, and 180 kg N ha⁻¹) and harvest management on switchgrass (harvested in August and postfrost) and NT-C (with and without 50% stover removal) in eastern NE. We measured SOC, aggregate stability, SMB-C, bulk density (BD), pH, P and K in the top 0–30 cm. Both NT-C and switchgrass increased SMB-C, SOC content, and aggregate stability over the 9 years, reflecting improvement from previous conventional management. However, the soils under switchgrass had double the percent aggregate stability, 1.3 times more microbial biomass, and a 5–8% decrease in bulk density in the 0–5 and 5–10 cm depths compared to NT-C. After 9 years, cumulative decrease in available P was significantly greater beneath NT-C (24.0 kg P ha⁻¹) compared to switchgrass (5.4 kg P ha⁻¹). When all measured soil parameters were included in the Soil Management Assessment Framework (SMAF), switchgrass improved soil quality index over time (ΔSQI) in all depths. NT-C without residue removal did not affect ΔSQI, but 50% residue removal decreased ΔSQI (0–30 cm) due to reduced aggregate stability and SMB-C. Even with best-management practices such as NT, corn stover removal will have to be carefully managed to prevent soil degradation. Long-term N and harvest management studies that include biological, chemical, and physical soil measurements are necessary to accurately assess bioenergy impacts on soils.

Keywords: harvest timing, no-till corn, P, K, N fertilizer, residue removal, soil C sequestration, soil organic C, switchgrass

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Introduction

Bioenergy production has increased exponentially over the past 30 years (U.S. Department of Energy, 2013) in part leading to a dramatic increase in US acreage planted to corn (Zea mays) USDA-NAAS, 2013 and consuming over 30% of the US corn production in 2009 (Robertson et al., 2011). The primary feedstock for producing cellulosic bioethanol, corn stover, is attractive due to the large quantity of biomass available (Karlen et al., 2011a, b). However, concerns have been raised about the long-term annual removal of 50% or more of the crop residue and its potential to decrease both plant and soil productivity while also increasing the potential for soil erosion—ultimately reducing future yields and decreasing soil organic carbon (SOC) content (Johnson et al., 2011; Karlen et al., 2011a, b).

Switchgrass (Panicum virgatum L.) is a perennial, native, C₄ grass capable of growing on a broad range of soil types and under non-irrigated conditions (Sander-son et al., 2006; Jokela et al., 2009; Monti, 2012). Fertilizer N requirements for switchgrass are generally low compared to corn and depend on yield potential, cultivar, and management practices (Vogel et al., 2002). Since switchgrass grows in association with mycorrhizal fungi it requires little, if any additional P (Brejda, 2000; Muir et al., 2001). Fertilizer rates of 120 kg N ha⁻¹ yielded between 10.5 and 12.6 Mg ha⁻¹ biomass in IA and NE with no increase in soil nitrate levels (Vogel et al., 2002).
A summary of 39 studies found that lowland switchgrass yields were often as high in unfertilized stands as in fertilized stands but upland switchgrass types responded to fertilizer to 100 kg N ha\(^{-1}\), although in many studies the amount of available soil N was not characterized (Wullschleger et al., 2010).

Switchgrass has been presented as an optimal biofuel with the potential to increase SOC stocks, decrease erosion, decrease fertilizer use, and consequently reduce greenhouse gas (GHG) emissions when it is assumed that there is no land conversion from the Conservation Reserve Program, native forest, or grassland (Adler et al., 2007; Davis et al., 2010; Robertson et al., 2011). Compared to corn, the perennial nature of switchgrass requires fewer tillage events and has greater belowground productivity, thereby increasing soil aggregation and reducing erosion potential (Jung et al., 2011). Less soil disturbance as well as lower N fertilizer inputs reduces GHG contributions to the atmosphere (Adler et al., 2007; Robertson et al., 2011). Due to its perennial, deep-rooted growth form, switchgrass can increase belowground C stocks (Liebig et al., 2008; Garten et al., 2010; Schmer et al., 2011; Follett et al., 2012), and thus reduce potential soil erosion. However, following conversion from conventionally managed cropland, production of no-till corn (NT-C) has resulted in similar soil C sequestration rates to that of switchgrass, both in the field (Follett et al., 2012) and based upon modeled SOC change (Robertson et al., 2011) compared to conventionally managed corn and corn soybean (Glycine max) rotations.

Accounting for agricultural management practices is crucial to accurately predict future effects of biomass removal on GHG flux and soil properties, including SOC (Adler et al., 2007; Robertson et al., 2011; Follett et al., 2012). Nitrogen fertilizer generally increases yields for both switchgrass and corn (Vogel et al., 2002; Varvel et al., 2008; Wullschleger et al., 2010; Follett et al., 2012). However, the relative importance of N fertilizer for SOC stocks will depend on the above- and belowground production allocation for switchgrass. Many perennial species allocate additional N to aboveground, rather than belowground growth and belowground root production decreases at high N fertilizer rates (Heggenstaller et al., 2009). In addition, the amount of aboveground biomass returned to the soil under corn could be greater than that returned under switchgrass. Depending on tillage practice and plant productivity, harvest rates for sustainable biofuel production (maintaining SOC stocks) of corn stover for biofuel are generally less than 50% (Wilhelm et al., 2007; Johnson et al., 2011) and harvesting the lower portions of the stalk contribute little to actual biofuel gain. Switchgrass harvest generally removes most aboveground biomass to a 10 cm stubble height and can be done in early season (August) or postfrost depending on desired nutrient content (Vogel et al., 2002). Harvesting switchgrass after frost allows nutrient translocation from the aboveground biomass to belowground plant structures, but potentially presents problems with harvest timing competition with that of grain crops (Vogel et al., 2002). Due to its perennial nature, switchgrass has the potential to alter nutrient cycling of N, P, and K as well as influence the soil microbial community—all functions that are crucial to continued crop productivity.

Although the importance of N fertilizer and harvest management practices on SOC stocks and other soil properties is well known (Robertson et al. 2011) and can be quite variable depending on geography (Schmer et al., 2011), the longer term impact (>5 years) of these practices on soil parameters is rarely quantified. Here, we examine the changes in soil parameters every 3 years [aggregate stability, soil microbial biomass (SMB), SOC, P, K, pH, and bulk density] to determine plant species, N and harvest effects on the potential sustained crop production for biofuels. We then use the Soil Management Assessment Framework to integrate these measured soil variables into an indicator of soil quality and assess the relative impact of these practices (Andrews et al., 2004). We hypothesize that: (i) switchgrass will have greater SOC, aggregate stability, SMB, available P and lower bulk density compared to NT-C; (ii) N fertilizer should increase SOC, aggregate stability, and SMB-C in both treatments due to increased biomass production; and (iii) residue removal in NT-C should decrease SOC, aggregate stability, SMB-C and available P, with a smaller decrease evident in the switchgrass August compared to the postfrost harvest.

**Material and methods**

**Site and experimental design**

The long-term switchgrass and corn experiment is located 50 km west of Omaha, NE at the University of Nebraska’s Agricultural Research and Development Center (latitude 41.151, longitude 96.40) (details in Follett et al., 2012). The climate is mesic with mean annual temperature of 9.16 °C and mean annual precipitation of 635 cm. Field soils were Yutan silty clay loam (fine-silty, mixed, superactive, mesic Pachic Argiudoll) and Tomek silt loam (fine, smectitic, mesic Pachic Hapludalf) with a slope less than 2%.

The experiment was established in 1998 on a marginally productive field that was conventionally farmed (tilled) since 1974 and for crops that included wheat, corn, soybean, milo, and oats. Marginal productivity was based on the fact that corn yields on the best managed plots were about 25% less than the Saunders County corn yields for nonirrigated corn. The site was also degraded in SOC, with 14.9 ± 3.2 g SOC kg\(^{-1}\) soil in
the 0–10 cm depth in 1998 (Table 1). For Midwestern mollisols, values under 20 g SOC kg⁻¹ soil indicate degraded soils compared to native sites with 50 g SOC kg⁻¹ soil or greater (Andrews et al., 2004). The study is a 9 year rainfed experiment comparing bioenergy crop species (corn and switchgrass), N fertilizer rates, and harvest practices (Follett et al., 2012). It is designed as a randomized complete block split-split plot experimental design with two cultivars of switchgrass (Trailblazer and Cave-in-Rock), and NT-C. Three N fertility treatments were randomly assigned within the main plots. Subplots are 30 m long × 18 m wide and are separated by 15 m wide alleys. From 2000 to 2007, N fertilizers on the switchgrass were 0, 60, and 120 kg N ha⁻¹ and on NT-C were 60, 120, and 180 kg N ha⁻¹. The 0N rate was used as a low input treatment only for switchgrass. In 2001, the switchgrass and NT-C subplots were split lengthwise into 9 m wide sub-subplots for harvest treatments (no residue removal or 50% residue removal for corn and August or post-frost harvest for switchgrass), after the 2001 soil sampling. No phosphorus (P) or potassium (K) fertilizer was applied during the experiment.

### Soil sampling and analyses

Soils were sampled in July 1998, May 2001, April 2004, and May 2007 from the 0–5, 5–10, 10–30 cm depths by excavating each increment of soil using a flat-bladed shovel as described by Follett et al. (2009). Soils were then transported to Fort Collins, CO or Lincoln, NE and refrigerated until processed. Soils were 2 mm sieved and all plant material >2 mm hand-picked from the soil. Moist subsamples were retained for microbial biomass and soil moisture content (105 °C) (Follett et al., 2007). Another subsample was oven-dried at 55 °C, mechanically ground to pass through a 0.2-mm sieve, and stored in glass containers until C analysis.

Physical (bulk density, wet aggregate stability) and chemical (pH, P, K) analyses were performed at the NRCS National Soil Testing Laboratory in Lincoln, NE, using established methods (USDA-NRCS (Natural Resources Conservation Service), 2004). Soil bulk density was determined using the Saran-coated clod method 3B1. Soil clods were cut from the excavated soil material to a suitable size (average of about 210 cm³) using a butcher knife, coated immediately with Saran F310, hung on a clothes line to dry, then placed in NRCS chambered boxes and transported to the laboratory. After desorption to 33 kPa, the clod was weighed in air to measure mass and in water to measure its volume and next dried at 110 °C with its mass and volume again determined. A correction is made for mass and volume of rock fragments and the Saran F310 coating with the BD value reported for <2 mm (<0.079 in) soil fabric (USDA-NRCS (Natural Resources Conservation Service), 2004). Wet soil aggregate stability (method 3F1a1a) was performed on soils sieved to 2 mm and wet-sieved on a 0.5 mm sieve and expressed as a percent soil mass (USDA-NRCS (Natural Resources Conservation Service), 2004). Bray soil phosphorus (P) (method 4D3), ammonium acetate-extractable K (method 4B1a1a), and pH (1:1 soil:water, method 4C1a2a) were also determined (USDA-NRCS (Natural Resources Conservation Service), 2004).

### Soil microbial biomass

Soil microbial biomass was determined on moist soils using the incubation-fumigation method (Jenkinson & Powell, 1976; Voroney & Paul, 1984) and described in detail in Follett et al. (2007). Briefly, duplicate laboratory replicates of soil samples were brought to −0.05 MPa and incubated at 30 °C for 10 days. Soils were fumigated using distilled chloroform at day 10 and incubated for an additional 10 days. Soil respiration was trapped in 1 M NaOH base traps and titrated with an excess of HCl.

### Soil C analyses

Total C and N concentration and δ¹³C were determined using a Europa Scientific automated nitrogen carbon analyzer (ANCA-NT) with a Solid/Liquid Preparation Module (Dumas combustion sample preparation system) coupled to a Europa 20-20 Stable isotope analyzer continuous flow isotope ratio mass spectrometer (Europa Scientific Ltd., Crewe, England).

All soils were checked for carbonates and where found were removed prior to analyses for organic C with addition of 0.03 M H₂PO₄, dried at 55 °C and ground (Follett et al., 1997). All analyses are expressed as oven dry weight (55 °C). The isotopic C analyses and the analyses for the total SOC were done at the same time on the same sample.

### Soil management assessment framework

We integrated the chemical, physical, and biological measurements into a single index of soil quality using SMAF (Andrews et al., 2004). The SMAF follows a three-step framework including (i) indicator selection, (ii) indicator interpretation, and (iii)
integration into a soil quality index (SQI) score. Briefly, data from seven soil properties were used for step one: SMB-C, aggregate stability, SOC, BD, pH, P, and K. Non-linear scoring algorithms were used for step two to assign a score for each property (ranging from 0 to 1, with 1 representing highest potential soil function). To ensure algorithms were appropriate for the edaphic, climatic, and management attributes associated with the study site, appropriate factor class assignments were selected based on categories in the SMAF. Individual normalized scores for each soil parameter (SOC, BD, etc.) were averaged to obtain an aggregated SQI score for each treatment and depth increment, with larger scores indicating higher SQI.

Statistics

Data were analyzed using a split-split plot design in Proc GLIMMIX in SAS version 9.3 (Cary, NC, USA). Fixed main treatment effects were plant, N × plant and harvest × plant within each depth. Replicate, replicate × plant and replicate × N × plant were considered random effects. Variables were tested for homogeneity of variance, normalcy and when necessary, log transformed to meet these criteria. Change over time (Δ) for all variables was assessed as significance from zero using p-values from the LSMEANS statement. Differences between treatment means were estimated with predetermined comparisons using ESTIMATE and LSESTIMATE. We report least squared means from the LSMEANS statement. Differences between treatment effects were plant, N plant and harvest effects. Statistical significances were determined using the method of least significant difference (LSD). A p-value of < 0.05 was considered significant.

Soil parameters over time

The field where this experiment was established was a marginally productive soil, typical of those suggested for growing perennial grasses for bioenergy. The field had an inherent high degree of variability between the field replicates (Follett et al., 2012). The largest treatment differences were observed in 2007 and we report treatment means from that year and yearly differences from 1998. No significant cultivar effects were observed between switchgrass varieties Cave-in-Rock and Trailblazer, so the data were combined and presented as switchgrass.

Results

Initial soil properties

Initial site characteristics indicated that the site was degraded and contained low SOC contents for Midwestern mollosols, with 14.9 ± 3.2 g SOC kg⁻¹ soil in the 0–5 cm depth in 1998 (Table 1). Soil organic C contents under 20 g C kg⁻¹ soil indicate degraded soils in this region (Andrews et al., 2004). Aggregate stability was 20.8 ± 8.6% and SMB-C was 312.5 ± 93.9 kg C ha⁻¹. Soil pH was 6.5 ± 3.4, bulk density 1.25 ± 0.8 g cm⁻³, and test K averaged 414.6 ± 103.8 mg kg⁻¹. Soil P was variable across the field, 11.68 ± 11.51 kg P ha⁻¹.

Soil microbial biomass

More SMB-C was observed in switchgrass plots compared to NT-C plots in the 0–5, 5–10, 10–30, and 0–30 cm depths in 2007 (P < 0.017 for all depths, Fig. 1a). Nitrogen fertilizer decreased SMB-C in both switchgrass and corn at the highest rates in the 0–5 cm depth (P < 0.002), but differed between species at depth and the combined 0–30 cm depth. Soil microbial biomass C was significantly lower at the 180 kg N ha⁻¹ fertilizer rate in NT-C compared to 60 kg N ha⁻¹ for the 0–5, 5–10, and 0–30 cm depths (P < 0.002). Intermediate N fertilizer in switchgrass (60 kg N ha⁻¹) had greater SMB-C than for either its 0 or its 120 kg N ha⁻¹ rate in the combined 0–30 cm layer, (P < 0.002, Fig. 1b). The 50% residue removal from NT-C decreased SMB-C 28% in the 0–5 (P = 0.0008) and increased SMB-C 10% in the 5–10 cm depth (P = 0.0020), but there was no harvest effects on switchgrass SMB-C (Fig. 1c).

Plant effects (NT-C vs. switchgrass) on SMB-C were evident as early as 2001 in the 0–5 cm layer, and moved deeper into the profile in 2004 (0–5 and 5–10 cm) and 2007 to 30 cm (0–5, 5–10 and 10–30 cm, data not shown). Switchgrass significantly increased ΔSMB-C from 1998 to 2001 and 2007 in the 10–30 cm (P = 0.020) depths (Fig. 2a). For each year, ΔSMB-C was significantly greater in switchgrass than NT-C (P = 0.058, P = 0.040, P = 0.027) in the 0–5 cm depths.

Aggregate stability

Averaged across N and harvest, switchgrass soils had significantly greater percent aggregate stability (35.5%) in the 0–5, 5–10 and 0–30 cm depths compared to NT-C (17.9%, Fig. 3a). There was no effect of N fertilization in 2007 (Fig. 3b). Harvest treatment altered aggregate stability with greater aggregate stability in the August switchgrass harvest compared to postfrost in the 0–5 cm depth. Although the NT-C with 50% residue removed had lower aggregate stability compared to the no residue removal treatment, this reduction was not significant (Fig. 3c).

In 2001, both NT-C and switchgrass increased Δ percent aggregate stability in the 0–5 cm depth by 13.4% and 34.9%, respectively, although this effect was only significantly greater than 0 under switchgrass (P = 0.036, Fig. 2b). Switchgrass increased Δ aggregate stability in all depths in 2004 (P = 0.015) and 2007 (P = 0.031), while NT-C had no significant effect on aggregate stability in any depth.

Bulk density

In 2007, bulk density was significantly lower under switchgrass compared to NT-C in the 0–5 (P = 0.008)
and 5–10 (P = 0.004) cm depth (data not shown). Soils
under the August switchgrass harvest had lower bulk
density (1.34 g cm\(^{-3}\)) than those under postfrost harvest
(1.41 g cm\(^{-3}\)) in the 5–10 cm depth in 2007 (P = 0.025).
NT-C significantly increased \(\Delta\) bulk density 0.05–
0.13 g cm\(^{-3}\) in the 0–5 cm depth in 2004–2007, while
there was no significant change beneath switchgrass
(Fig. 2c). In 2007, all depths under NT-C, except
5–10 cm, had a significant increase in \(\Delta\) bulk density.

**SOC**

By 2007, differences in SOC content (g C kg\(^{-1}\) soil)
between plant species and harvest treatments were small
and rarely significant (except 5–10 cm, Fig. 2d). Both
NT-C and switchgrass significantly increased \(\Delta\)SOC content
in 2007 in all depths, except in the 5–10 cm and 10–
30 cm for NT-C (Fig. 2d). Nitrogen fertilizer significantly
increased switchgrass SOC (g C kg\(^{-1}\) soil) in the 0–5 cm
depths at the 60 kg N ha\(^{-1}\) (P = 0.051) and 120 kg
N ha\(^{-1}\) rates (P = 0.008, data not shown).

All plant, N and harvest treatments increased \(\Delta\)SOC
(Mg C ha\(^{-1}\)) in the 0–30 cm depth except 0N switch-
grass (both harvests) and 60N NT-C RR (Table 2). Nitro-
gen fertilizer addition of 60 kg N ha\(^{-1}\) significantly
increased \(\Delta\)SOC (Mg C ha\(^{-1}\)) in the 0–5 and 10–30 cm
depths and 120 kg N ha\(^{-1}\) significantly increased \(\Delta\)SOC
(Mg C ha\(^{-1}\)) in the 0–5 and 5–10 cm depths under
switchgrass. Increasing fertilizer from 60 to 120 and
180 kg N ha\(^{-1}\) significantly increased \(\Delta\)SOC (Mg
C ha\(^{-1}\)) in the 0–5 cm depth in NT-C (Table 2). How-
ever, there were no significant differences between
treatments (plant, N, or harvest effects) in \(\Delta\)SOC (Mg
C ha\(^{-1}\)) for the 0–30 cm depth.

**Phosphorus**

Available soil P decreased from 1998 to 2007 (\(\Delta\)P), but this
effect was dependent on plant species and N fertilization
rate (Fig. 2e). In 2007, switchgrass had significantly small-
er \(\Delta\)P decrease (−5.38 kg P ha\(^{-1}\)) compared to NT-C
(−24.04 kg P ha\(^{-1}\)) in the entire profile (P = 0.005). In
NT-C soils, increased N fertilization rate decreased \(\Delta\)P
from −13.10 kg P ha\(^{-1}\) in the 60N treatment under NT-C
to 11.58 kg P ha\(^{-1}\) under the 180N in the 0–5 cm depth
(P = 0.0007, data not shown). This trend was observed for
both species in the 10–30 cm and 0–30 cm depths. In the
NT-C 0–30 cm depth, Available P increased from
−71.81 kg P ha\(^{-1}\) under 60N to 12.08 kg P ha\(^{-1}\) under
180N (P < 0.0001, data not shown).

**Potassium**

Available soil potassium (K) was only affected by
harvest treatment (data not shown). Soils beneath
switchgrass harvested in August had decreased soil K
compared to the postfrost harvest in the 0–5 (P = 0.001),
5–10 (P = 0.09), and 0–30 cm (P = 0.021) depths in 2007,
although these effects were not significantly different
from zero. From 1998 to 2007, there were no significant
plant or N effects (Fig. 2f, data not shown), but the
switchgrass August harvest had greater \(\Delta\)K compared
to the postfrost harvest in the 0–5 cm depth (−0.13,
0.03 mg K kg\(^{-1}\) soil, respectively, data not shown).
In 2007, soil pH was greater beneath switchgrass (6.08) compared to NT-C (5.26) in the 0–5 cm depths ($P = 0.017$, Table 3). N fertilizer decreased soil pH ($P = 0.0003$) in the surface soils under both switchgrass (6.47, 6.15, and 5.61 under 0, 60, and 120 kg N ha$^{-1}$) and NT-C (5.91, 5.15, and 4.17 under 60, 120, and 180 kg N ha$^{-1}$). There was a small harvest effect under switchgrass in the 5–10 cm depth where postfrost harvest pH was greater than for the August harvest ($P = 0.006$). From 1998 to 2007, increasing N fertilizer rate decreased ΔpH in the surface depths (0–5 and 5–10 cm) for both NT-C and switchgrass ($P < 0.0001$, data not shown).

### Soil management assessment framework

After 9 years, plant species, N fertilization and harvest all impacted soil quality. Switchgrass soils had better soil quality as indicated by larger SQI values compared to NT-C in all depths ($P = 0.002$, Table 4). The increase in SQI under switchgrass was primarily due to an increase in SOC, aggregate stability, SMB-C, and BD scores despite a decrease in P score at low N rates (Table 5). Although NT-C did increase SOC, aggregate stability, and BD scores from 1998, pH indicators decreased.

Nitrogen fertilization decreased SQI scores under NT-C, but had no significant effect in switchgrass, likely driven by the decrease in pH scores (Table 5). NT-C had significantly reduced SQI values in all depths (0–5, 5–10, 10–30, 0–30 cm) under the 180 kg N ha$^{-1}$ fertilization compared to 120 and 60 kg N ha$^{-1}$ ($P < 0.015$). The pH score decreased from 0.98 under 60 kg N ha$^{-1}$ to 0.71 in the 180 kg N ha$^{-1}$ under NT-C NRR (Table 5).

Residue removal with NT-C decreased SQI in the 0–5 cm depth ($P = 0.004$). This effect was a result of lower SOC, aggregate stability and SMB-C indicator scores (Table 5). Averaged over N rate, harvest timing for switchgrass had contradictory effects by depth, with the 5–10 cm having greater SQI under August harvest (65.3 vs. 62.7, $P = 0.063$), but 10–30 cm having greater SQI harvest postfrost (49.7 vs. 52.3, $P = 0.012$).

The SQI detected plant effects as early as 2001 in the surface soils and moved deeper through the profile over time. Switchgrass soils had significantly greater SQI values compared to NT-C in 2001 ($P = 0.014$) and 2004 ($P = 0.005$) in the 0–5 cm depths (data not shown). This plant effect became more pronounced over time with the 5–10 cm depth significant in 2004 ($P = 0.058$), and the 10–30 cm depth significant in 2007 ($P = 0.050$, data not shown).

Expressed as a change from 1998, switchgrass increased ΔSQI in all depths and years (Fig. 4). NT-C with no residue removed had no significant effect on ΔSQI in individual depths except for 0–5 cm in 2004. In 2007, NT-C with 50% residue removal significantly decreased ΔSQI in the 0–5 and 0–30 cm depth (−3.42, $P = 0.007$).

It is worth noting that despite greater negative ΔP under NT-C (Fig. 2e), indicator scores for P are greater than for switchgrass (Table 5). Soil K showed no change in SQI score for any treatment over time.

**Fig. 1** Soil microbial biomass (kg C ha$^{-1}$) in 2007 for corn and switchgrass under N addition rates (0, 60, 120 kg N ha$^{-1}$ for switchgrass and 60, 120, and 180 kg N ha$^{-1}$ for NT-C) with two harvest treatments for switchgrass (August and postfrost) and two residue treatments for NT-C (no residue removal (NRR) and 50% residue removal (50RR)). Panel ‘a’ compares crops over N & harvest treatments; ‘b’ compares crop × N rate means, and ‘c’ compares crop × harvest treatments. Letters indicate significant differences within depth, ($\alpha = 0.10$).
Conversion to conservation management practices

Both NT-C and switchgrass increased SOC content (g C kg\(^{-1}\)) and SOC sequestration (Mg C ha\(^{-1}\)) over this 9 year study and confirmed the importance of best-management practices for improving SOC on degraded or marginally productive soils. Conversion from conventional tillage to NT systems increases SOC and soil aggregation by decreasing soil disturbance and microbial C mineralization (e.g. Six et al., 1999, 2004; Denef et al., 2004). Management practices that decrease soil disturbance (such as NT) and/or increase C input (conversion into perennial switchgrass systems) increase SOC after conversion from...
conventional tillage systems assuming comparable crop productivity (West & Post, 2002; Ogle et al., 2005). Other researchers have found that both switchgrass (Liebig et al., 2005, 2008; Schmer et al., 2011) and NT-C (see references in West & Post, 2002) can sequester soil C after conversion from conventional cropping systems (Robertson et al., 2011). Although this rapid C sequestration will decline with time, after initial conversion, Follett et al. (2012) reported soil C sequestration rates of 2 Mg C yr⁻¹ for NT-C and switchgrass treatments in these fields from 1998 to 2007 (to a depth of 150 cm).

Switchgrass increased soil aggregate stability and SMB-C

Despite little difference in total SOC (g C g⁻¹ soil or Mg C ha⁻¹) between switchgrass and NT-C, after 9 years, switchgrass soils had 130% greater SMB-C and double the percent aggregate stability. These plant effects moved deeper within the soil profile over time, reflecting the development and maturity of switchgrass rooting systems and associated soil microflora. After 3 years, plant effects were only observed in the surface (0–5 cm horizon), after 6 years, in the 0–5 and 5–10 cm horizons, and after 9 years the entire 0–30 cm depth had greater SMB-C under switchgrass compared to NT-C. Perennial grasslands and pastures have greater root production resulting in more exudation and rhizodeposition compared to annual cropping systems (Culman et al., 2010). Lower disturbance from cultivation as well as greater resource availability results in greater soil microbial biomass (Culman et al., 2010). There are few direct studies examining switchgrass SMB, and frequently they use different methods. Using Brightfield microscopy, Watrud et al. (2013) found active bacterial biomass greater in switchgrass and grassland sites compared to sorghum, but no differences in active fungal biomass. A recent study by Liang et al. (2012) found no significant difference between corn and switchgrass, but a significant increase under prairie or restored prairie in microbial lipid C concentration (a proxy for microbial biomass) in the 0–10 cm depth across 10 corn and 9 switchgrass sites in southern Wisconsin (averaging 10 years management). They found higher amounts of fungi and arbuscular mycorrhizal fungi markers in the prairie soils (Liang et al., 2012). Ma et al. (2000) found that switchgrass increased microbial biomass 168% compared to initial values after only 2 years switchgrass growth (0–15 cm) using the chloroform fumigation-incubation method. Perennial systems generally increase fungal biomass, which is important for soil aggregate formation (Bossuyt et al., 2001) and long-term soil C sequestration (Six et al., 2006).

Soil aggregates form around fresh organic C input and are held together by microbial exudates (Tisdall & Oades, 1982; Six et al., 2006), so it is no surprise that both aggregate stability and SMB-C were greater beneath switchgrass compared to NT-C. Identifiable plant material, comprised primarily of root biomass in the 0–30 cm depths was ten times greater under switchgrass than NT-C in 2007 and was directly related to SMB-C (data not shown, $R^2 = 0.61$, $P = 0.013$). The larger, perennial root system of switchgrass compared to corn

![Fig. 3 Aggregate stability (%) in 2007 for corn and switchgrass under N addition rates (0, 60, and 120 kg N ha⁻¹) for switchgrass and 60, 120, and 180 kg N ha⁻¹ for NT-C) with two harvest treatments for switchgrass (August and postfrost) and two residue treatments for NT-C (no residue removal (NRR) and 50% residue removal (50RR)). Panel 'a' compares plants over N & harvest treatments; 'b' compares plant x harvest treatments and 'c' compares plant x harvest treatments. Letters indicate significant differences within depth, (z = 0.10).](image-url)
Table 3  Soil pH in 2007 for switchgrass and NT-C for all depths. N addition rates were 0, 60, and 120 kg N ha\(^{-1}\) for switchgrass and 60, 120, and 180 for NT-C. The two harvest treatments August harvest, postfrost (PF) harvest for switchgrass and no residue removal (NRR) and 50% residue removal (50RR) for NT-C.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Plant</th>
<th>Harvest</th>
<th>N application rate (kg N ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>0–5</td>
<td>Switchgrass</td>
<td>August</td>
<td>6.52 ± 0.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PostFrost</td>
<td>6.42 ± 0.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>6.47 ± 0.18</td>
</tr>
<tr>
<td></td>
<td>NT-Corn</td>
<td>NRR</td>
<td>6.03 ± 0.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50RR</td>
<td>5.80 ± 0.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>5.92 ± 0.18</td>
</tr>
<tr>
<td>5–10</td>
<td>Switchgrass</td>
<td>August</td>
<td>6.42 ± 0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PostFrost</td>
<td>6.37 ± 0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>6.39 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>NT-Corn</td>
<td>NRR</td>
<td>6.20 ± 0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50RR</td>
<td>6.40 ± 0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>6.30 ± 0.2</td>
</tr>
<tr>
<td>10–30</td>
<td>Switchgrass</td>
<td>August</td>
<td>6.53 ± 0.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PostFrost</td>
<td>6.55 ± 0.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>6.54 ± 0.14</td>
</tr>
<tr>
<td></td>
<td>NT-Corn</td>
<td>NRR</td>
<td>6.33 ± 0.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50RR</td>
<td>6.63 ± 0.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>6.48 ± 0.14</td>
</tr>
</tbody>
</table>

Table 4  SQI lsmeans and standard errors in 2007 for switchgrass and NT-C for N addition rates (0, 60, and 120 kg N ha\(^{-1}\) switchgrass and 60, 120, and 180 NT-C) with two harvest treatments August harvest, postfrost harvest for switchgrass and no residue removal (NRR) and 50% residue removal (50RR) for NT-C. Larger scores indicate better soil quality.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Plant</th>
<th>Harvest</th>
<th>N application rate (kg N ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>0–5</td>
<td>Switchgrass</td>
<td>August</td>
<td>77.4 ± 2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PostFrost</td>
<td>76.6 ± 2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>77.0 ± 2.6</td>
</tr>
<tr>
<td></td>
<td>NT-Corn</td>
<td>NRR</td>
<td>65.8 ± 2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50RR</td>
<td>66.2 ± 2.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>66.0 ± 2.6</td>
</tr>
<tr>
<td>5–10</td>
<td>Switchgrass</td>
<td>August</td>
<td>65.5 ± 3.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PostFrost</td>
<td>63.9 ± 3.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>64.7 ± 3.1</td>
</tr>
<tr>
<td></td>
<td>NT-Corn</td>
<td>NRR</td>
<td>52.5 ± 3.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50RR</td>
<td>52.8 ± 3.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>52.6 ± 3.1</td>
</tr>
<tr>
<td>10–30</td>
<td>Switchgrass</td>
<td>August</td>
<td>52.3 ± 2.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PostFrost</td>
<td>52.9 ± 2.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>52.6 ± 2.8</td>
</tr>
<tr>
<td></td>
<td>NT-Corn</td>
<td>NRR</td>
<td>47.7 ± 2.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50RR</td>
<td>47.7 ± 2.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>47.7 ± 2.8</td>
</tr>
</tbody>
</table>
Table 5  Individual parameter SQI scores for 1998 (98) and 2007 (07) and P-values for the change over time (Δ) for switchgrass and NT-C in the 0–5 cm depth. N addition rates were 0, 60, and 120 kg N ha\textsuperscript{-1} for switchgrass and 60, 120, and 180 for NT-C with two harvest treatments August harvest, postfrost (PF) harvest for switchgrass and no residue removal (NRR) and 50% residue removal (50RR) for NT-C. Larger scores indicate better soil quality. P-values indicate treatment effects for the change in SQI score (Δ) from 1998 to 2007.

<table>
<thead>
<tr>
<th>Plant</th>
<th>0.245</th>
<th>0.044</th>
<th>0.275</th>
<th>0.705</th>
<th>0.433</th>
<th>0.019</th>
<th>ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>0.036</td>
<td>0.124</td>
<td>0.008</td>
<td>0.016</td>
<td>0.035</td>
<td>0.418</td>
<td>ns</td>
</tr>
<tr>
<td>Harvest</td>
<td>0.483</td>
<td>0.055</td>
<td>0.004</td>
<td>0.002</td>
<td>0.887</td>
<td>0.769</td>
<td>ns</td>
</tr>
<tr>
<td>N × Harvest</td>
<td>0.402</td>
<td>0.605</td>
<td>0.956</td>
<td>0.004</td>
<td>0.909</td>
<td>0.932</td>
<td>ns</td>
</tr>
</tbody>
</table>
contributes greater root biomass, belowground C input and aggregate-stabilizing exudates contributing to greater aggregate stability and soil microbial biomass in the former (Ma et al., 2000; Jung et al., 2011). These results emphasize the importance of belowground plant root allocation for SOC, aggregate stability, and microbial biomass.

**N fertilization and residue removal decreased SMB-C**

Increasing N fertilizer rates in NT-C decreased SMB-C in our study, a response observed by other researchers (Biederbeck et al., 1996; Sarathchandra et al., 2001; Liebig et al., 2002). This observation has been attributed to direct effects of toxicity, soil acidity, and osmotic effects of ammonia (Biederbeck et al., 1996; Lupwayi et al., 2012), but could also be due to decreased belowground plant allocation to arbuscular mycorrhizal fungi under greater N availability (Treseder, 2004). Lupwayi et al. (2011, 2012) found that low levels of N (80 kg N ha\(^{-1}\) for corn, and 60 kg N ha\(^{-1}\) for barley) stimulated SMB-C through increased plant productivity, but under high N fertilizer rates, free N in solution decreased solution pH and decreased SMB-C. In this study, aboveground yields of both corn and switchgrass increased with increasing N fertilizer rate (Follett et al., 2012). Accordingly, the observed decrease in SMB-C with N fertilization is likely due to the accumulation of N and decrease in soil pH over the experimental timeframe.

**Phosphorus depletion in low N corn**

The difference between NT-C and switchgrass in net available soil P accumulation or loss reflects cumulative uptake, biomass removal, and recycling. Switchgrass had a relatively small decrease in Δ available P over 9 years (averaging \(-5.4\) kg P ha\(^{-1}\), 0–30 cm) compared to NT-C (\(-24.0\) kg P ha\(^{-1}\)) and was within the range described by Schmer et al. (2011) after 5 years in North and South Dakota (2.5–14.2 kg P ha\(^{-1}\), 0–30 cm). Switchgrass has a relatively low P requirement and some P may be translocated belowground after a killing frost and recycled the following year (Heggenstaller et al., 2009).

The relatively high available P concentrations observed in NT-C soils with greater N fertilization reflects greater corn P uptake and recycling and/or indirect effects of decreased soil pH. The negative Δ available P was greatest under NT-C with the lowest N fertilizer rate (60 kg N ha\(^{-1}\)), suggesting plant mining of soil P under low nutrient levels. At higher N fertilization rates, Δ available P was positive possibly due to the repeated return of relatively high P corn residues to the soil. Corn has high P uptake (Eghball et al., 2003) which is proportional to soil N availability (Ziadi et al., 2007) and N fertilization increases corn shoot P concentration (Follett et al., 1974; Ziadi et al., 2007). Higher available soil P may also be due to decreased pH under higher N fertilizer applications, since P extractability increases with increasing soil acidity. The SQI score for P was greater in NT-C compared to switchgrass and increased with increasing N fertilizer application under both plants, reflecting greater available P with lower pH.

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**Fig. 4** Cumulative plant and harvest effects on Δ soil quality index (ΔSQI) for corn (NT-C) and switchgrass (SG) under two harvest treatments for switchgrass August harvest (Aug) or postfrost harvest and two residue treatments for NT-corn [no residue removal (NRR), 50% residue removal (50RR)] at the 0–5, 5–10, 10–30, and 0–30 cm depths. Letters indicate significant differences between plant species within depth. Asterisks indicate significance from zero, (\(a = 0.10\)).

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Soil quality index

Switchgrass increased the combined ΔSQI, reflecting improvement from baseline conventional tillage management. However, with no residue removal, NT-C did not affect ΔSQI, and with 50% residue removal, ΔSQI decreased. Despite greater plant biomass removal rates for switchgrass compared to NT-C, the greater root biomass inputs from the perennial system increased SOC, soil aggregate stability, and SMB-C, increasing ΔSQI. In this rainfed climate, the perennial system with low disturbance appeared to balance switchgrass biomass removal and improve soil quality indices. These findings confirm numerous individual studies documenting the benefits of perennial crops on SOC stocks, soil aggregation and SMB-C (Ma et al., 2000; Culman et al., 2010; Jung et al., 2011).

Given the increase in SOC (Mg C ha⁻¹) from initial baseline in NT-C, the lack of improvement in SQI was surprising. Adoption of conservation tillage should build soil quality in surface layers following conversion from conventional tillage from increased SOC storage and reduced bulk density (West & Post, 2002; Ogle et al. 2005). However, decreased soil pH and BD indicator scores offset increased SOC in the no residue removal treatment. Even after 9 years of NT-C, soil aggregation was still low, bulk density was higher, and lower SMB beneath 50% residue removal NT-C, all contributed to negative ΔSQI.

There is concern about the long-term viability of corn stover removal on sustained soil productivity (Karlen et al., 2011a, b). We observed that 9 years of 50% residue removal in NT-C decreased ΔSQI by three times (0–30 cm) compared with no residue removal, due to decreased aggregate stability and SMB-C scores. These effects were only observed after 9 years, confirming the importance of NT management in minimizing negative impacts of bioenergy production. However, to maintain soil productivity with long-term residue removal, smaller removal rates are required (Johnson et al., 2011). Stover is essential in forming soil aggregates in surface soils which protects soils from erosion (Johnson et al., 2011). Without this C input, soils under long-term stover removal are at risk for greater erosion. In these mesic systems, corn residue removal will have to be carefully balanced not to deplete the soil resource.

The SMAF assessment detected agricultural management effects as early as 3 years after treatment establishment, reflecting the sensitivity of the individual measured indicator metrics. The index also detected changes through the profile with time as switchgrass roots developed. This illustrates the value of using an integrative index of measured soil parameters to assess management effects, as many field studies measuring soil C, aggregation and bulk density need a minimum of 5 years to observe treatment effects (West & Post, 2002; Liebig et al., 2008; Schmer et al., 2011). The most sensitive indicators here were aggregate stability, SMB-C, SOC content, bulk density, and pH, detecting treatment changes between plant species, N rate and harvest practices. The SMAF framework has been successfully used to assess land use, tillage, crop rotations (Jokela et al., 2009), soil type (Andrews et al., 2004), corn stover removal (Karlen et al., 2011a, b), and watershed variability (Karlen et al., 2008; Stott et al., 2011).

Conclusions

Best-management practices such as NT or perennial cropping systems are essential for conserving the soil resource while providing biomass for bioenergy. After conversion from conventionally managed systems, these practices increased SOC stocks, soil aggregation and SMB-C. Despite the improvement in these metrics from a degraded soil baseline, NT-C with no residue removed increased soil bulk density and decreased pH, resulting in no ΔSQI change. With 50% residue removal NT-C, reductions in aggregate stability and SMB-C resulted in a net negative ΔSQI for the 0–30 cm depth over the 9 years. Corn stover residue removal will need to be carefully evaluated, even under conservation practices to prevent soil degradation. Switchgrass, with a perennial rooting system, less soil disturbance from field management, and consequently much greater aggregate stability and SMB-C, increased ΔSQI. This emphasizes the need for long-term studies that include a diverse set of field measurements—biological, chemical, and physical—to accurately assess the impact of bioenergy feedstock production on soils. Future work should quantify bioenergy management effects on soil C and edaphic properties deeper in the soil profile.

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References


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