Cropping Systems Effects on Improving Soil Carbon Stocks of Exposed Subsoil

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Removal of topsoil from glaciated-till-derived soils exposes infertile subsoil that is poorly suited to crop production (Olson, 1977). Subsoil is very low in SOC content, which is a key component of soil fertility (Bauer and Black, 1994). Several techniques can be implemented to improve SOC stock of such soils. Practices that incorporate no-till or minimum tillage coupled with perennial or extended cropping systems and adequate fertility can increase soil C and restore the productivity of degraded soils. It has been documented that reclamation of soils such as mine soils that are similar to these topsoil-striped areas in chemical and physical conditions that include a balanced fertility program and topsoil placement showed an improvement in physical properties such as bulk density and SOC concentration (Shukla et al., 2004). Topsoil removal associated with road construction can alter soil physical, chemical, and biological properties significantly. Restoration of such disturbed soils can improve soil productivity and soil C stocks (Lal et al., 1998). Carbon sequestration is an effective management strategy for degraded soils, which can raise their productivity and offset CO₂ emissions from fossil fuel combustion (Lal, 2004). Therefore, reclamation techniques and cropping systems should be implemented to determine the best strategies for improving soil C stocks in exposed subsoil. Perennial grasses are known to contribute significantly to the improvement of soil C stocks (Post and Kwon, 2000). The increase in soil C stocks of degraded soils will depend on the productivity of the cropping system (Akala and Lal, 2001; Lal, 2004).

Liebig et al. (2004) reported that SOC contents are greater under a switchgrass system than with row-crop cultivated lands. The greater SOC content under switchgrass can be detected at deeper depths than row crops, which can be attributed to its large root biomass (Liebig et al., 2004; Ma et al., 2000a). Generally, the effectiveness of grass in improving soil C stocks can be partially attributed to the slower decomposition of roots, which will increase C longevity in soil (Puget and Drinkwater, 2001). Roots play a significant role in promoting soil micro- and macroaggregate formation and stability, where SOC is protected (Chevallier et al., 2004). Furthermore, the release of organic compounds by roots increases the binding of soil particles and stabilization of SOC (Bronick and Lal, 2005). Therefore, even switchgrass harvested for bio-energy uses could potentially improve soil C stocks (Ma et al., 2000a; Zan et al., 2001). Additionally, root decomposition is important in aggregate formation and particulate organic matter carbon (POM-C) dynamics (Gale et al., 2000; Puget and Drinkwater, 2001). The labile POM-C fraction can be a sensitive indicator of SOC change and soil quality (Cambardella and Elliot, 1992; Chan et al., 2002). A large-scale conversion of grasslands to row-crop agriculture or any soil disturbance can result in tremendous losses or translocation of the SOC fraction (Lal et al., 1998).

Abbreviations: CS, corn–soybean rotation; DOY, day of the year; MBC, microbial biomass carbon; POM-C, particulate organic matter carbon; S5, switchgrass burned every 5 yr; SA, switchgrass, respectively. Microbial biomass C was 200% greater in the switchgrass cropping system produced 3.47 and 2.33 Mg ha⁻¹ more aboveground biomass than soybean and corn, respectively. Switchgrass had 14 Mg ha⁻¹ greater root biomass than corn or soybean. As a result, potential C input from the S5 switchgrass treatment was 6.08 and 6.71 Mg ha⁻¹ greater than corn and soybean, respectively. Microbial biomass C was 200% greater in the switchgrass cropping systems (S5 and SA) than in the corn–soybean rotation. The switchgrass system is an effective strategy for improving exposed subsoil C fractions and providing greater potential C input through a more extensive root system than the corn–soybean rotation.

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Table 1. Soil pH and bulk density of exposed subsoil under three cropping systems in the 60-cm soil profile.

<table>
<thead>
<tr>
<th>Cropping system†</th>
<th>0–15 cm</th>
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<td></td>
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<td>7.49</td>
<td>7.43</td>
<td>7.43</td>
<td>1.40</td>
</tr>
</tbody>
</table>

† SA is switchgrass burned annually, S5 is switchgrass burned every 5 yr, and CS is corn–soybean rotation.

1998), where a significant portion of the labile fraction (POM-C) is associated with stable macroaggregates (Cambardella and Elliott, 1992). Soil disturbance enhances mineralization of soil organic C and N fractions by destroying soil aggregates and enhancing soil aeration (Cambardella and Elliott, 1993).

Prudent management of row-crop fields can increase soil C stocks. Reduced tillage, nutrient management, and water conservation are management practices that can be implemented to promote C sequestration (Lal, 2004). Higher residue-producing crops such as corn can increase SOC better than crops that produce less residue, such as soybean (Paul et al., 1999).

Cropping systems can impact soil microbial biomass, which is an important component of the SOC pool and may be an early indicator of SOC changes (Powlson and Brookes, 1987). The microbial biomass is highly variable, however, and difficult to quantify (Hargreaves et al., 2003). Ma et al. (2000a) found that microbial biomass C (MBC) content can increase as much 168% 2 yr after switchgrass establishment on previously cropped soils. It has also been found that the size of the microbial biomass pool can influence rates of soil CO₂ emission (Franzluebbers et al., 1996), but the amount of available substrate will ultimately determine the size of the MBC pool (Wang et al., 2003). Changes in residue management can alter MBC as well, and burning residues will result in a reduction in MBC (Powlson and Brookes, 1987).

The overall objective of this study was to evaluate the long-term impact of a corn–soybean rotation and switchgrass systems in improving soil C stocks of exposed subsoil by evaluating crop residue C input and soil CO₂-C output in addition to soil C pool improvement indicators such as soil microbial biomass and SOC fractions.

MATERIALS AND METHODS

Site Description and Management

This study was conducted on a borrow site near Webster City, IA, during the growing seasons of 2003 and 2004. Borrow sites are areas where topsoil has been removed and subsoil mined for construction purposes. The predominant soil on this site was a Nicollet loam (Aquic Hapludoll) with Clarion loam (Typic Hapludoll) on the hillsides. The topsoil was removed from this 2.43-ha site in 1977 for road construction purposes. The exposed subsoil was a calcareous, unweathered and unoxidized glacial till of Cary age (Khalaf, 1984). A portion of the area was converted to a research site, and three cropping system treatments were established on the exposed subsoil. The cropping systems were: (i) corn–soybean rotation (CS), (ii) switchgrass burned annually (SA), and (iii) switchgrass burned every 5 yr (S5). The experimental design was a randomized complete block with four replications. Each plot was 9 m wide by 18 m long. Bulk densities and pH values for the three cropping system treatments are summarized in Table 1. Monthly precipitation and maximum air temperatures at the research site are summarized in Fig. 1.

The corn–soybean rotation was established in 1978 and was managed during this study as follows: Each fall the corn–soybean plots were tilled to a depth of 40 cm with a two-shank deep ripper. The deep ripper shanks were spaced 45 cm apart. In the spring, the plots were disked once at a depth of 7 cm for seedbed preparation. In 2003, Pioneer 35P17 corn was planted 20 May, day of year (DOY) 140, at 45724 seeds ha⁻¹ on 76-cm row spacing. In 2004, Pioneer 92B38 soybean was planted on 1 July (DOY 182) at 450,000 seeds ha⁻¹ on 76-cm row spacing. The fertility use on this research site since 1978 was conducted by initially applying 112 kg N ha⁻¹ of P and 112 kg ha⁻¹ of K. The application rates of P and K were based on soil tests for P and K concentrations that were conducted every other year since 1978. Phosphorous and K soil tests at the site showed high levels of P and K of an overall average of 49 and 192 mg kg⁻¹, respectively (Dr. Stan Henning, site manager since 1978, personal communication, 2006). Therefore, no P or K was applied during either corn or soybean year in 2003 and 2004. In 2003, corn plots on this research site received approximately 170 kg N ha⁻¹. Historically, N was applied to corn since 1978 at an average rate of 170 kg N ha⁻¹ on all plots (Potter, 1980; Khalaf, 1984). Weed control consisted of row cultivation and chemical herbicides (one application of glyphosate [N-(phosphonomethyl)glycine] at a rate of 2.32 L ha⁻¹ in 2003 and 2004).

Fig. 1. Monthly (a) maximum air temperature and (b) precipitation distribution during 2003 and 2004 growing seasons for the research site from a nearby weather station.
Field Soil Carbon Dioxide Emission Measurements

Carbon dioxide emissions from the soil surface were measured by placing the soil chamber of a LI-6400 infrared gas analyzer (LI-COR Corp., Lincoln, NE) over polyvinyl chloride (PVC) rings that were pressed 3 cm into the soil. The PVC rings had an inside diameter of 10 cm, and 2 cm of the rings remained above the soil surface. Four PVC rings were placed near the center of each plot. For the corn–soybean rotation, two rings were placed in the crop row and two were placed between the rows. Switchgrass vegetation was clipped and removed from the inside of the rings to avoid measuring plant respiration. The mean of the four rings was considered to be the CO$_2$ emission rate for the entire plot. Carbon dioxide measurements were recorded every 7 to 14 d from 5 June to 29 October (DOY 156–302) in 2003 from all treatments. In 2004, soil CO$_2$ measurements were taken in the switchgrass treatments from 22 May to 5 November (DOY 142–309), and in the corn–soybean rotation from 6 July to 5 November (DOY 187–309) because of a delay in soybean planting. All CO$_2$ measurements were taken between 1000 and 1400 h. No measurements were taken for 48 h following the row cultivation in 2003. Soil temperature and soil moisture at the 5-cm depth were measured concurrently with CO$_2$ measurements. Soil temperature was measured with a thermometer attached to the LI-6400 analyzer, and volumetric soil moisture content was measured with a TRIME-FM time domain reflectometer (Mesa Corp., Medfield, MA).

Cumulative CO$_2$ emissions for the growing season were calculated as follows:

$$\text{Cumulative \ CO}_2 (\text{kg ha}^{-1}) = \sum_{i=1}^{n} X_i + X_{i-N} + X_{i-N^2} + \ldots + X_{i-N}$$  \[1\]

where $X$ is the CO$_2$ emission rate (kg ha$^{-1}$ d$^{-1}$), $n$ is the last CO$_2$ measurement during the growing season, $i$ is the first CO$_2$ measurement in the season, and $N$ is the number of days between two consecutive CO$_2$ rate measurements. Cumulative soil CO$_2$ emissions were then converted to megagrams CO$_2$-C per hectare.

Soil Microbial Biomass Carbon

Soil samples for soil MBC determination were collected from all of the cropping systems in 2004 when the row crop treatment reached the V6 growth stage. A composite soil sample of 10 cores was taken from each plot at a depth of 15 cm. The soil samples were brought back to the laboratory, passed through a 4-mm sieve, and stored in a 4°C cold room overnight. Soil MBC was determined by the fumigation extraction method (Horwath and Paul, 1994). Fifty-gm moist soil samples from the three cropping system treatments were fumigated with ethanol-free CHCl$_3$ for 24 h in a vacuum desiccator. The soil samples were extracted for 30 min with 100 mL of 0.5 M K$_2$SO$_4$ and then filtered through Whatman no. 42 filter paper (Whatman Int., Maidstone, UK). A similar extraction was performed on the unfumigated soil samples while the others were being set up for fumigation. The extractant (K$_2$SO$_4$) alone was also filtered to determine the background level of C in the filter paper and extractant. Carbon recovered in the extract was measured with a Shimadzu TOC-5050 carbon analyzer (Rydalmere, New South Wales, Australia). Microbial biomass C was calculated on an oven-dry weight basis.

Laboratory Soil Incubation

The remainder of the soil from the samples collected for microbial biomass analysis was used for laboratory soil incubation. A static incubation–titrimetric procedure (Zibilske, 1994) was used for this experiment. The soil samples were taken out of the cold room, passed through a 2-mm sieve, and allowed to air dry. Twenty grams of each soil sample was placed in 20-mL borosilicate vials. Approximately 7 g of water was added to the vials to achieve 60% water-filled pore space. Each vial with soil was placed into a 0.9-L wide-mouth glass jar along with a 10-mL scintillation vial containing 1.0 mL of 2 M NaOH as a base CO$_2$ trap. Approximately 3 to 5 mL of water was added to the glass jars to maintain proper humidity levels. The lids of the glass jars were closed to seal the contents from the outside atmosphere. A base trap was also placed in a jar that contained no soil, to act as a control (blank). The glass jars were then placed in a dark incubation room at 30°C. The amount of CO$_2$–C evolved was determined by titration. Two milliliters of 1 M BaCl$_2$ and two to three drops of phenolphthalein were added to the base traps and titrated with 1 M HCl through a digital microburette until the indicator showed neutral pH. After titration, a new base trap was added to each jar. Titrations were performed on Days 1, 3, 5, 7, 14, 21, 28, 35, 42, 49, 56, 63, and 77 after initiation of soil incubation.

Soil inorganic N (NO$_3$–N and NH$_4$–N) concentration was determined before and after the incubation period using the KCl extraction method (Mulvaney, 1996). Ten grams of soil was extracted with 50 mL of 2 M KCl for 30 min. The supernatant liquid was then filtered through Whatman no. 42 filter paper. The inorganic N concentration of the filtrate was measured with a Lachat Quick Chem 8000 FIA+ (Lachat Instruments, Loveland, CO).

Soil Organic Carbon and Soil Total Nitrogen Determination

In the spring of both 2003 and 2004, soil samples were collected from all of the cropping system treatments at soil depths of 0 to 15, 15 to 30, 30 to 45, and 45 to 60 cm. A composite soil sample consisting of 10 cores was taken from each depth within each treatment using a soil probe with an inside diameter of 1.9 cm. Additionally, soil samples were collected from four adjacent fallow areas for baseline comparisons. Soil samples were placed in a −4°C freezer immediately after collection until soil analysis was performed. Soil samples for bulk density determination were collected at the same time for each depth according to the procedure outlined by Doran and Mielke (1984). Three separate soil cores, 2 to 10 cm long, were taken with the same soil probe for each depth per plot. The soil cores were weighed and oven dried at 104°C for bulk density determination.

Before conducting soil C analysis, the soil samples were defrosted, passed through a 2-mm sieve, and allowed to air dry. Two 10-g subsamples were taken from each soil sample. The first subsample was ground with a mortar and pestle and analyzed for total carbon (TC) and total nitrogen (TN) contents by dry combustion using a LECO CHN 2000 analyzer (LECO Corp., St. Joseph, MI). Soil pH was determined using a 1:1 (soil/water) dilution. If soil pH was >7.1, inorganic C content was determined by using a modified pressure calcmeter method (Sherrod et al., 2002) and subtracted from the soil total C content values determined initially by the LECO CHN 2000 analyzer.

The second soil subsample was used in the soil POM-C fractionation procedure (Cambardella and Elliot, 1992; Kruse, 2005). The soil subsample was dispersed with sodium hexametaphosphate solution and passed through a 53-μm sieve. The water was evaporated from the slurry that passed through the sieve by placing it in a forced...
air oven at 50°C for 72 h. The dried soil material was ground and analyzed for associated mineral fraction carbon (MF-C) concentration by dry combustion using the LECO CHN 2000 analyzer. Particulate organic matter C content was calculated by subtracting MF-C content from SOC content. The C content of each fraction was calculated on an equivalent soil mass basis by using the bulk density.

**Potential Total Carbon and Total Nitrogen Input from Aboveground and Root Biomasses**

Crop residue was collected each fall from all of the cropping systems after mechanical harvest of the row crop was completed. A 1-m² frame (1 m by 1 m) was randomly placed near the center of each plot, and the entire residue within the frame was collected and placed in mesh bags. To collect residue from the switchgrass cropping systems, all of the biomass within the frame was clipped at the soil surface and then collected. Residue from all cropping systems was dried at 64°C for 7 d, weighed, and then ground using a Wiley Mill Model 2 grinder (Arthur H. Thomas Co., Philadelphia, PA) and passed through a 2-mm screen. Total C and N concentrations of the crop residue were determined by dry combustion using the LECO CHN 2000 analyzer, and the values were multiplied by the biomass to determine potential TC and TN inputs.

Root biomass samples were collected when the row crop treatment reached the R1 growth stage. Corn root samples in 2003 were obtained by excavating all roots from the top 30 cm of soil in a 1-m² frame on the ground, removing the vegetation, and then excavating all of the roots in the top 30 cm of soil. All roots were taken back to the laboratory and soaked in water for 24 h. After soaking, they were rinsed of any excess soil, then placed in a 64°C forced air dryer for 7 d. Corn root weight density in 2003 was calculated as follows:

$$RWD = \frac{RDM}{(\pi \times CR^2 \times D)} \quad [2]$$

where RWD is root weight density (g cm⁻³), RDM is root dry matter (g), RL is row length (cm), RW is row width (cm), and D is depth (cm). Switchgrass root weight density in 2003 was calculated using Eq. [2] by substituting the dimensions (1 m by 1 m) of the frame for RL and RW.

In 2004, soil cores for determining soybean and switchgrass root biomasses were obtained. The aboveground biomass was cut at the soil surface, and three 6.3-cm i.d. soil cores were collected from the top 30-cm soil depth from each plot of soybean rows and switchgrass treatments. The switchgrass and soybean root samples were stored in a −4°C freezer until they were washed with a hydro pneumatic elutriation system (Smucker et al., 1982). Soybean and switchgrass roots were dried in a 64°C forced air oven for 7 d. Soybean and switchgrass root weight densities in 2004 were calculated as follows:

$$RWD = \frac{RDM}{(\pi \times CR^2 \times D)} \quad [3]$$

where CR is core radius (cm). Switchgrass, corn, and soybean root biomass was calculated as follows:

$$RB = RWD \times D \times 100 \quad [4]$$

where RB is root biomass (Mg ha⁻¹), and 100 is a conversion factor for area and mass.

Oven-dried plant materials including both aboveground and root biomasses from all cropping systems were weighed, ground using a Wiley Mill Model 2 grinder (Arthur H. Thomas Co., Philadelphia, PA), and passed through a 2-mm screen. Total C and total N concentrations were determined by dry combustion using the LECO CHN 2000 analyzer, and the values were multiplied by the aboveground and root biomasses to determine potential TC and TN inputs.

**Statistical Analysis**

All experiments were analyzed as randomized complete blocks with four replications. Cropping systems were treated as fixed factors and replications were treated as random. A mixed model procedure with repeated measures was used for the daily field soil CO₂ emission rate analysis of variance (SAS Institute, 2005). The repeated factor was day and the subject was the interaction of replication and soil depth. A compound symmetry covariance structure was used for the repeated measures. All other experiments were analyzed with the general linear models (GLM) procedure of SAS. Tukey’s least-squares means adjusted for multiple comparisons at \(P < 0.05\) was used. Two different methods of sample collection were used for switchgrass treatment root biomass each year as outlined above. Therefore, the two sampling methods were compared using the switchgrass data in paired \(t\)-tests and mean separation comparisons to assess any differences in root biomass estimation. No significant differences were observed between the two methods of determining the root biomass.

**RESULTS AND DISCUSSION**

**Field Soil Carbon Dioxide Emissions**

During the 2003 growing season, the two switchgrass cropping systems, SA and S5, had greater daily soil CO₂ emission rates than the CS cropping system, which was corn, on eight out of 13 sampling dates (Fig. 2c). Additionally, the SA cropping system had greater soil CO₂ emission rates than the S5 cropping system on DOY 156 and 163. During the 2004 growing season, soil CO₂ emissions were the greatest from the SA cropping system for 40% of the sampling dates (Fig. 3c). The CS cropping system, which was soybean, and the S5 cropping system had similar rates of soil CO₂ emission, except on DOY 196 and 208. In both years, soil CO₂
emissions were similar from all of the cropping system treatments once soil temperatures began to cool, with the exception of DOY 260 in 2003 (Fig. 2b, 2c, 3b, and 3c). These results are similar to those of Tufekcioglu et al. (1999), who found greater rates of soil respiration from switchgrass in riparian buffers than from nearby row crop fields.

The differences between soil CO$_2$ emission rates of the CS cropping system and switchgrass cropping systems in 2003 were greatest early in the growing season (Fig. 2c). This may be due to the fact that annual crops have small root systems at the beginning of their life cycle. The brief period of extremely dry soil conditions in the CS cropping system also may have delayed development of the corn root system. The unexpected late planting of soybean in 2004 prevented early season measurements, but initial soil CO$_2$ emissions from soybean once it was established were significantly less than from the switchgrass cropping systems (Fig. 3c). In both years, greater soil CO$_2$ emissions from subsoil with both cropping systems generally occurred when soil moisture approached field capacity (Fig. 2a and 3a) and soil temperature was at the warmest for the year. As the soil temperature began to cool, no differences were found in CO$_2$ emission rates, approximately DOY 233 in 2003 and DOY 264 in 2004 (Fig. 2b and 3b). These findings are consistent with those of Bajracharya et al. (2000), who found that soil CO$_2$ emission rates from eroded soil increased when soil temperatures were the warmest.

Both years, cumulative CO$_2$–C emissions were the greatest from the SA cropping system, followed by the S5 and CS cropping systems (Fig. 4). Even though soybean was planted late in 2004, cumulative soil CO$_2$–C emissions were similar to those from corn in 2003. The greater cumulative soil CO$_2$–C may have been due to the larger root biomass (Table 2) and greater MBC content of the switchgrass cropping systems (Fig. 5). Root biomass is known to play a significant role in releasing organic compounds that bind soil particles and stabilize SOC (Chevallier et al., 2004; Bronick and Lal, 2005). This may have improved the soil environment and contributed positively to CO$_2$–C emission. Microbial biomass C content of the CS cropping system was approximately half that of the switchgrass cropping systems (S5 and SA). Additionally, the S5 cropping system had 20% more MBC than the SA cropping system. Ma et al. (2000a) also found greater MBC in switchgrass cropping systems than row crops. The larger MBC content of the S5 cropping system may be due to the greater amount of detritus on the soil surface because of less frequent burning. Powshon and Brookes (1987) also found less MBC in crops that annually had the same of their life cycle. The brief period of extremely dry soil conditions in the CS cropping system also may have delayed development of the corn root system.

The results of the laboratory soil incubation support the field soil CO$_2$ emission findings. The SA and S5 cropping systems had greater rates of CO$_2$–C emission than that of the CS cropping system from Days 3 to 35 after incubation (Fig. 6). After Day 35, CO$_2$–C emission rates were similar for all cropping system treatments. Rates of CO$_2$–C emission were similar from the SA and S5 cropping systems during the entire incubation period. Cumulative CO$_2$–C emissions from the SA and S5 cropping systems were almost two times greater than CO$_2$–C emissions from the CS cropping system (Fig. 7). Before soil incubation, the CS cropping system had a greater inorganic N content (3.93 mg kg$^{-1}$) than the switchgrass cropping systems SA and S5 (0.71 and 0.97 mg kg$^{-1}$, respectively), but 77 d after soil incubation, net mineralization of organic N as indicated by mineral N concentration was similar for all of the cropping systems (Fig. 8). This suggests that the organic N mineralization in the SA and S5 treatments was as effective as in the CS rotation even though the CS treatment has greater initial inorganic N content.

**Potential Total Carbon and Total Nitrogen Input from Aboveground and Root Biomasses**

Analysis of variance of aboveground and root biomasses across years showed no difference between the two switchgrass cropping systems; therefore, the biomass mean of both switchgrass cropping system treatments was compared with that of the corn–soybean rota-
tion. Statistical analysis also showed no difference between the two methods of root biomass sample collection. Additionally, aboveground biomass potential TC input from the SA cropping system was not included in the calculation due to annual burning.

The unfavorable growing conditions in the soil including the lack of nutrient availability and high bulk density of the subsoil resulted in poor aboveground biomass production of the switchgrass, corn, and soybean; however, switchgrass produced 3.47 and 2.33 Mg ha\(^{-1}\) more aboveground biomass than soybean and corn, respectively (Table 2). The aboveground biomass values are considerably lower than those reported for the same cropping systems in topsoil by Tufekcioglu et al. (2003). Even though switchgrass aboveground biomass production was impaired by the subsoil growing conditions, the root system biomass did not appear to be affected. Root biomass of the switchgrass was 15.13 Mg ha\(^{-1}\), which was 8 Mg ha\(^{-1}\) greater than its aboveground biomass production. Switchgrass root biomass was also considerably greater than the root biomass of corn or soybean (Table 2). Ma et al. (2000b) also found the root biomass of switchgrass to be quite large, up to 28 Mg ha\(^{-1}\) in some soils. In this study, the root biomass was only calculated to the 30-cm soil depth due to negligible root biomass growth beyond that depth in all cropping systems. The restricted root system development beyond the 30-cm depth is largely due to high bulk density and lack of nutrient availability of the subsoil in this study area (Table 1). Tufekcioglu et al. (2003) also found that 73% of root biomass could be found in the top 35 cm of topsoil.

Corn aboveground biomass had the greatest C/N ratio, followed by switchgrass and then soybean (Table 2). Carbon/nitrogen ratios of the root biomasses followed the same trend as the aboveground biomasses. Tufekcioglu et al. (2003) also found soybean aboveground and root biomasses to have lower C/N ratios than switchgrass, but found greater C/N ratios in switchgrass biomasses than corn biomasses. The greater C/N ratio of corn than switchgrass in their study may be attributed to the N fertilizer the corn received and better topsoil condition.

The total (aboveground + root) potential TC input was greater from switchgrass than from corn or soybean, due in large part to the massive root biomass of the switchgrass (Table 2). Several other investigators (e.g., Liebig et al., 2004; Ma et al., 2000a, 2000b) have also suggested that the large root system of switchgrass is a key component of C input and accumulation.

### Soil Organic Carbon and Total Nitrogen

Analysis of variance of both years' soil C fraction data showed no significant differences between the 2 yr; therefore, the data of the 2 yr were combined for the final analysis.

Soil organic C and associated MF-C and POM-C contents were similar for all cropping systems across all soil depths (Table 3). This is in contrast to the findings of Liebig et al. (2004), who found greater SOC content in a switchgrass system than crop...
fields. One explanation is that poor subsoil physical conditions and lack of nutrient availability may contribute significantly to a poor aboveground biomass production for all cropping systems in this site (Porter, 1980). Additionally, the scheduled burnings of the switchgrass cropping-system treatments removed new and decaying detritus as a potential source for some nutrient input. The inherently nutrient-deficient subsoil condition at this site may have been a limiting factor for SOC buildup; Zan et al. (2001) reported that C accumulation under a switchgrass system is highly dependent on site conditions, and greater C accumulation can be expected on more fertile sites. It has also been reported that changes in SOC under switchgrass occur much more slowly than increases in MBC and soil CO$_2$-C emissions (Ma et al., 2000a).

All cropping systems had similar TN contents, however, and the S5 cropping system had a greater C/N ratio in the 0- to 15-cm soil depth (Table 4). In contrast, the S5 cropping system had greater TN content and lower C/N ratios than the SA and CS cropping systems in the 15- to 60-cm soil depths. This may be due to the greater amount of decaying detritus on the soil surface in the S5 cropping system. Powlson and Brookes (1987) also found less TN in cropping systems where residue is annually burned.

CONCLUSIONS

Aboveground biomass production of switchgrass and corn–soybean cropping systems is impaired by the poor growing conditions and the lack of nutrient availability of subsoil. Switchgrass can produce a large root biomass in subsoil, but it is limited in depth to 30 cm. Switchgrass cropping systems can potentially contribute greater C input to the soil than a corn–soybean rotation, primarily due to its large and well-developed, mature root system each season. It was also observed that switchgrass cropping systems improved subsoil MBC by approximately 200% that of corn- and soybean-based rotations.

Larger root systems and greater MBC may cause greater soil CO$_2$-C emissions from subsoil with switchgrass cropping systems than subsoil with corn–soybean rotation. This difference in emissions can be attributed to a larger MBC pool, which may lead to greater SOC mineralization in subsoil within switchgrass cropping systems compared with corn–soybean rotations.

Twenty-five years after the establishment of these cropping systems on exposed subsoil, there are no significant differences in soil C fractions between the cropping systems, regardless of the greater potential C input from switchgrass. It must be noted that the increase in SOC for the soil depth 0 to 60 cm during the past 25 yr was 0.80, 0.84, and 0.92 Mg ha$^{-1}$ yr$^{-1}$ for CS, SA, and S5 cropping systems, respectively. This suggests that C accumulates very slowly compared with increases in MBC, and the properties of subsoil may play a significant role in soil-C dynamics. These findings demonstrate the effectiveness of using a switchgrass cropping system and a well-managed rotation.
Table 4. Soil organic carbon (SOC), soil total nitrogen (TN) contents, and C/N ratios of exposed subsoil under three cropping systems in the 60-cm soil profile.

<table>
<thead>
<tr>
<th>Treatment†</th>
<th>0–15 cm</th>
<th>15–30 cm</th>
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</thead>
</table>
| § SA is switchgrass burned annually, S5 is switchgrass burned every 5 yr, and CS is corn–soybean rotation.
| † Soils were cropped with the following system: SA = switchgrass burned annually, S5 = switchgrass burned every 5 yr, CS = corn–soybean rotation.
| ‡ Means with the same letter within each sample depth are not different at P ≤ 0.05.
| $ Soil organic C and soil total N contents of the control were determined to estimate soil C and N content before treatment initiation.

 aged corn–soybean rotation in restoring and improving the soil C stock of exposed or degraded poor subsoil. The significant improvement in soil C fractions of degraded subsoil with these cropping systems present an important management option that can be used under similar conditions.

REFERENCES


Control§ | 2.85 | 0.66 | 1.40 | 0.70 | 0.27 | 0.24 | 0.15 | 0.21 | 10.55 | 2.72 | 9.33 | 3.33 |